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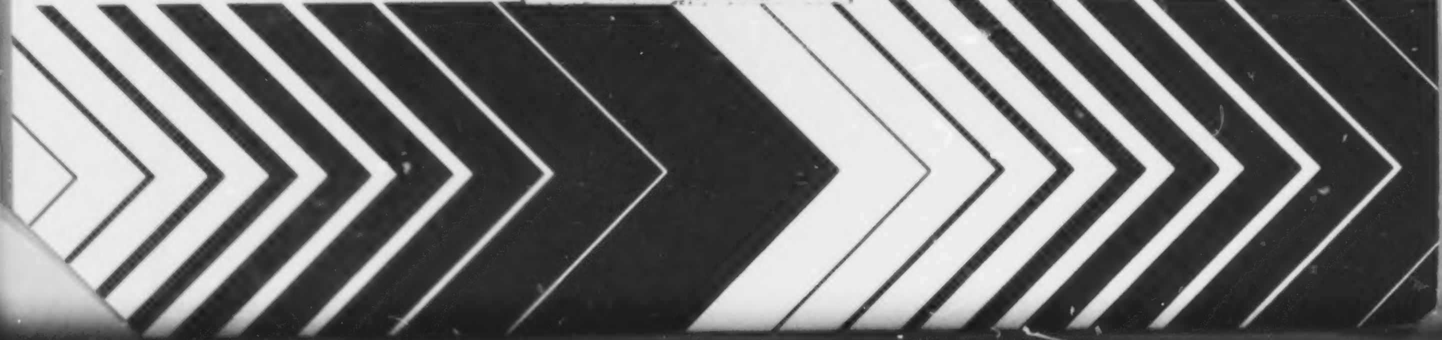

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Irrigation return flows in the Upper Colorado River Basin carry large salt loads as a result of contact with the saline soils and the marine derived geologic substratum. The Grand Valley of western Colorado is a major contributor to the salinity problems of the basin and is, therefore, a logical region to test the effectiveness of agricultural salinity control alternatives. This study emphasized the implementation of on-farm salinity control alternatives; primarily evaluating irrigation scheduling, furrow irrigation, sprinkler irrigation, and trickle irrigation. Border irrigation was also evaluated, but was not implemented as part of this study. The cost-effectiveness of the various on-farm alternatives in the Grand Valley is summarized and presented in this report.

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FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the Agency's effort involves the search for information about environmental problems, management techniques and new technologies through which optimum use of the Nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of these facilities, the Robert S. Kerr Environmental Research Laboratory is responsible for the management of programs to: (a) investigate the nature, transport, fate and management of pollutants in groundwater; (b) develop and demonstrate methods for treating wastewaters with soil and other natural systems; (c) develop and demonstrate pollution control technologies for irrigation return flows; (d) develop and demonstrate pollution control technologies for animal production wastes; (e) develop and demonstrate technologies to prevent, control or abate pollution from the petroleum refining and petrochemical industries; and (f) develop and demonstrate technologies to manage pollution resulting from combinations of industrial wastewaters or industrial/municipal wastewaters.

This report contributes to the knowledge essential if the EPA is to meet the requirements of environmental laws that it establishes and enforce pollution control standards which are reasonable, cost effective and provide adequate protection for the American public.

William C. Galegar

William C. Galegar
Director
Robert S. Kerr Environmental
Research Laboratory

PREFACE

This report is the second in a series of three reports resulting from U.S. Environmental Protection Agency Grant No. S-802985 entitled, "Implementation of Agricultural Salinity Control Technology in Grand Valley." This report is concerned with the evaluation of furrow, border, sprinkler and trickle irrigation as individual salinity control measures. The first report in this series has the same title as the grant and details the experimental design and the procedures used to collect data on several types of on-farm improvements, field drainage, canal and lateral linings and irrigation management practices (such as irrigation scheduling) as salinity control measures. The third report of this series "Best Management Practices for Salinity Control in Grand Valley" develops the methodology for determining the cost-effectiveness of individual salinity control measures, as well as a complete package of salinity control measures that should be implemented in the Grand Valley.

Another research project conducted in Grand Valley and largely funded by the U.S. Environmental Protection Agency has provided the necessary background in soil chemistry to support the cost-effectiveness analysis in the above three reports. This second project, "Irrigation Practices, Return Flow Salinity and Crop Yields," was supported by EPA Grant No. S-800687. Two reports resulted from this effort. The first report, "Irrigation Practices and Return Flow Salinity," focuses upon the prediction of subsurface irrigation return flow salinity. The second report, "Potential Effects of Irrigation Practices on Crop Yields in Grand Valley" focuses upon the impact of various irrigation practices in determining crop yields, with particular emphasis on maize (*Zea Mays L.*) and wheat.

ABSTRACT

Irrigation return flows in the Upper Colorado River Basin carry large salt loads as a result of contact with the saline soils and the marine derived geologic substratum. The Grand Valley of western Colorado is a major contributor to the salinity problems of the basin and is, therefore, a logical region to test the effectiveness of agricultural salinity control alternatives. This study emphasized the implementation of on-farm salinity control alternatives; primarily evaluating irrigation scheduling, furrow irrigation, sprinkler irrigation, and trickle irrigation. Border irrigation was also evaluated, but was not implemented as part of this study. The cost-effectiveness of the various on-farm alternatives in the Grand Valley is summarized and presented in this report.

This report is the second in a series of reports submitted in fulfillment of Grant No. S-802985 by Colorado State University under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period February 18, 1974 to February 17, 1977 and work was completed as of June 17, 1977.

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LIST OF ABBREVIATIONS AND SYMBOLS

ac -- acre, (43,560 ft^2) one acre equals 0.405 hectare
AF -- acre-foot, volume of water to cover one acre a depth of one foot, one acre-foot equals 0.1233 hectare-meters
BTU -- British Thermal Unit
cal/gm -- calories per gram
cfd -- cubic feet per day
cfs -- cubic feet per second, volume flow rate of water, one cfs equals 0.0283 cubic meter per second
cmd -- cubic meter per day
CMI -- Colorado Miner's Inch, one Colorado Miner's Inch equals 0.74 liters per second
cms -- cubic meters per second, one cubic meter per second equals 35.31 cfs
degrees C or °C -- centigrade temperature (also called Celsius) scale
degrees F or °F -- Fahrenheit temperature scale
ft -- feet, unit of length, one foot equals 0.3048 meters
gm -- gram, 454 grams equal one pound
gpm -- gallons per minute, volume flow rate of water, one gallon per minute equals 0.631 liters per second
ha -- hectare, metric unit of area, one hectare equals 2.471 acres
ha-m -- hectare-meter, volume of water to cover one hectare to a depth of one meter, one ha-m equals 8.108 AF
hr -- hour, 60 minutes
hp -- horsepower, one horsepower equals 7.460 x 10^{-5} erg/sec
in -- inch, one inch equals 2.54 centimeters
km -- kilometer, metric unit of length, one kilometer equals 0.621 miles
kPa -- kilopascal, metric unit of pressure, 6.9 kilopascal equals one psi
lb -- pound (mass)
lph -- liters per hour, volume flow rate of water
l/min -- liters per minute, volume flow rate of water

l/s -- liters per second, volume flow rate of water

m -- meter

m^3/s -- cubic meters per second, volume flow rate of water

me/l -- milliequivalents per liter

mg/l -- milligrams per liter, equal to one ppm

mi -- mile, one mile equals 1.609 kilometers

mm -- millimeter

mph -- miles per hour, velocity

N/m -- Newton per square meter, unit of pressure, one N/m^2 equals one Pascal (6.9 kPa equals one k)

ppm -- parts per million

psi -- pounds force per square inch, unit of pressure

sec -- seconds, time

UCC -- Christiansen's Uniformity Coefficient (Christiansen, 1942)

UCH -- Hawaiian Sugar Planters Association Uniformity Coefficient (Hart, 1961)

UCL -- Linear Uniformity Coefficient (Karmeli, 1977)

yd -- yard, unit of length, one yard equals 0.9144 meters

yd^3 -- cubic yard, unit of volume, one cubic yard equals 0.7646 cubic meters

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The cooperation of all the landowners and irrigators on the project who contributed labor, shared costs and expended much effort for the construction and operation of the lateral and on-farm improvements is greatly appreciated. Their willingness to participate in this investigation is undoubtedly one of the major factors for the degree of improvement which was achieved.

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Finally, the efforts and advice given by the EPA Project Officer, Dr. James P. Law, Jr., have been extremely helpful in the successful pursuit of this project. He has generously given of his time to cooperatively achieve the goals of the project.

SECTION 1

INTRODUCTION

PROBLEM STATEMENT

Approximately 10 million metric tons (11 million tons) of salts are delivered each year in the water supply serving the Lower Colorado River Basin (Figure 1). These salts reach Hoover Dam in about 1.36 million hectare-meters (11 million acre-feet) of water. Studies have indicated that roughly 37 percent of this salt load is contributed by irrigated agriculture in the Upper Colorado River Basin (Figure 2). Present salinity concentrations necessitate treatment of water for both municipal and industrial uses throughout the Lower Basin. In fact, at times, concentrations approach the tolerance of many high-value crops such as citrus, requiring the use of excessive quantities of water for leaching and expensive water management programs.

This situation is expected to become even more serious, especially when the many planned upstream water development projects are constructed. Thus, a program for reduction of mineral pollution is urgently needed in order to protect existing water users from quality degradation during low flow periods and to prevent the serious restriction of future basin-wide economic development. Due to the relatively large salinity contribution from agriculture, it is obviously one sector in which to begin implementation of technologies that will reduce the salt loading from these areas.

Since the Grand Valley of Colorado is the largest contributor of salts per hectare of irrigated land in the Upper Colorado River Basin, it was a logical place to begin investigating salinity control alternatives. The irrigated portions of the Grand Valley have an estimated salinity contribution averaging from 450,000 to 800,000 metric tons of salt annually to the Colorado River. These salts are a direct result of the deep percolation from irrigated farm lands and seepage from unlined canal and lateral water delivery systems. Examination of district and canal records show that this contribution has been fairly constant over the past sixty years. Elkin (1976) has estimated that the additional natural salinity contributions from the area has an upward limit of about 10 percent of the

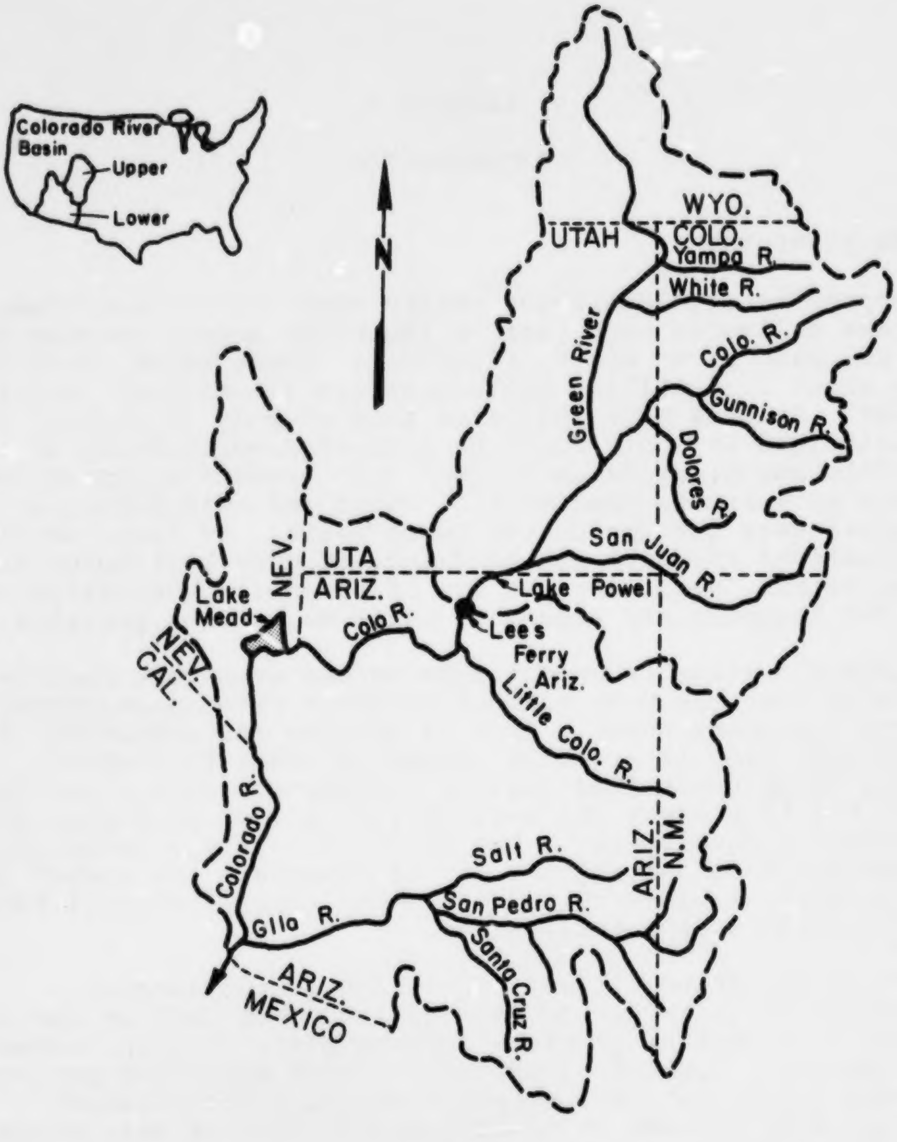
Colorado River Basin
Upper
Lower
N
WYO.
UTAH
COLO.
Yampa R.
White R.
Colo. R.
Green River
Gunnison R.
Dolores R.
San Juan R.
NEV.
UTA
ARIZ.
Lake Powel
Lake Mead
Colo R.
Lee's Ferry Ariz.
NEV.
CAL.
Little Colo. R.
Colorado R.
Salt R.
ARIZ.
N.M.
San Pedro R.
Gila R.
Santa Cruz R.
ARIZ.
MEXICO

Figure 1. The Colorado River Basin.

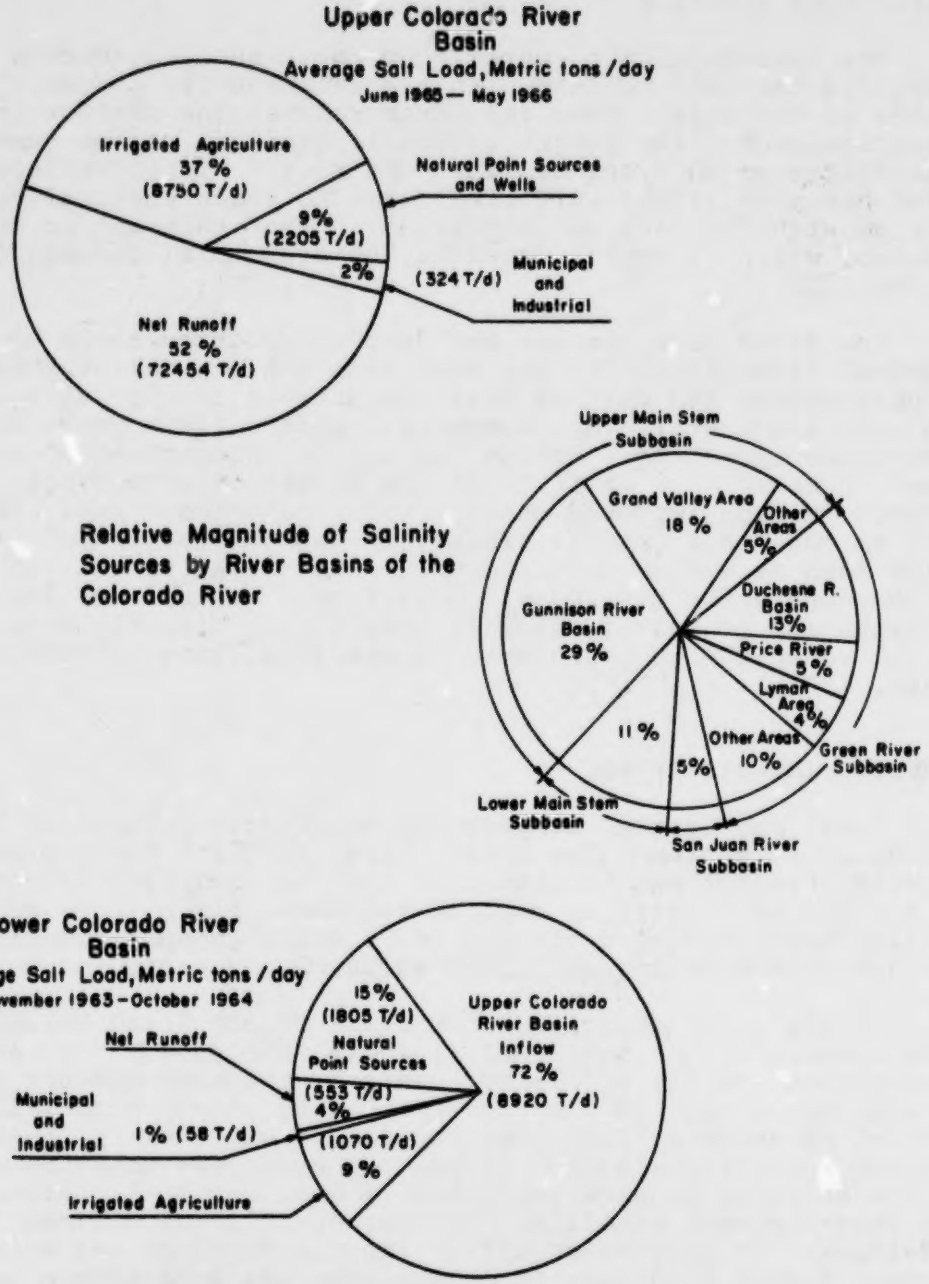

Figure 2. Relative magnitude and sources of salt in the Colorado River Basin (USDI, FWPCA, 1970, Appendix A).

salt loading from Grand Valley, or a maximum of about 80,000 metric tons annually.

The introduction of water from these surface sources dissolves the salt contained in the saline soils and marine shales of the area. When the water reaches the shallow groundwater reservoir, the slight hydraulic gradient causes some groundwater to be displaced into the river. This displaced water has usually had sufficient time to reach chemical equilibrium with the salt concentration in the shale and/or cobble aquifer, which is approximately 8,700 mg/l total dissolved solids (TDS).

The water from seepage and deep percolation tends to reach chemical saturation with the very abundant natural sources of soluble gypsum and calcite that are present in the soils and geologic substrata. The concentration of salts appears to be controlled by geologic conditions and is independent of seepage rates (Duke et al., 1976). If the amount of groundwater is reduced through improved on-farm water management practices, as well as canal and lateral lining, the concentrations of other salts such as sodium chloride will rise slightly, but not enough to compensate for the reduction in flows. Therefore, the net contribution to salt loading is essentially directly proportional to the reduction in groundwater flows (Skogerboe, McWhorter, and Ayars, 1978b).

PREVIOUS INVESTIGATIONS

Canal and lateral seepage can be greatly reduced by lining the delivery system. The Grand Valley Salinity Control Demonstration Project was initiated in 1968 to study the effectiveness of linings as a salinity control measure. Since then, additional studies have been conducted on field drainage and scientific irrigation scheduling as viable salinity reduction technologies.

In 1967, the irrigation companies of the Grand Valley became aware of the potential financial burden which could be placed upon the Valley's water users by salinity damages downstream, especially if they were forced to comply with salinity control measures at their own expense. Consequently, they began efforts to initiate action based on the concept that abatement of the salinity problem would have state, regional, national, and international benefits. Furthermore, it was claimed "that development of irrigation within the Grand Valley was done without intent of damage to others, and was done within existing laws and regulations and, therefore, the Valley's water users should not be penalized for their actions by laws and regulations enacted after the fact." With this in mind, the irrigation companies formed a cooperative organization called the Grand Valley Water Purification Project, Inc. and petitioned the

Federal Water Quality Administration for 70 percent matching funds to demonstrate canal lining as a salinity control measure. This money was forthcoming, and in 1968 the Agricultural Engineering Department of Colorado State University was contracted to perform the technical evaluation regarding the effectiveness of canal lining in reducing the Grand Valley's salt load to the Colorado River.

The particular demonstration area was selected because it contained lands served by the majority of irrigation companies in the Valley, and their cooperation after the project would be needed to implement the proposed changes on a valley-wide scale. The location of the demonstration area is shown in Figure 3, and a close up of the area is shown in Figure 4. After completion of this initial project, the canal companies reorganized into the Grand Valley Canal Systems, Inc. and remained active. Presently, their main purpose is to collectively represent the irrigation interests of the Valley.

Canal and Lateral Lining

The present demonstration area is one of three areas of study included in the initial investigation. The initial phase of the project involved the determination of the seepage rates from the canals and laterals in the three test areas. The ponding technique was employed to assure reliability of the results.

The results of this study indicated that canal and lateral lining in the test area reduced salt inflows to the Colorado River by about 4,260 metric tons (4,700 tons) annually. The bulk of this reduction is attributable to the canal linings, but the greater importance of lateral linings is clearly indicated. The length of laterals (600 kilometers), plus the total head ditches (1,640 kilometers), is about eight times greater than the length of canals (286 kilometers) in the Valley. The economic benefits to the Lower Basin water users alone exceeded the costs ($350,000 construction plus $70,000 administration) of this project. Consequently, it was concluded that conveyance lining in areas such as the Grand Valley, where salt loadings reach 18 metric tons or more per irrigated hectare, are a feasible salinity control measure. The local benefits accrued from reduced maintenance, improved land value, and other factors add to the feasibility of conveyance linings as a salinity management alternative. The results of this project are reported in detail in "Evaluation of Canal Lining for Salinity Control in Grand Valley," Report EPA-R2-72-047 (Skogerboe and Walker, 1972).

Irrigation Scheduling

An irrigation scheduling project was initiated in 1972 in the demonstration area as a salinity control measure. Since a

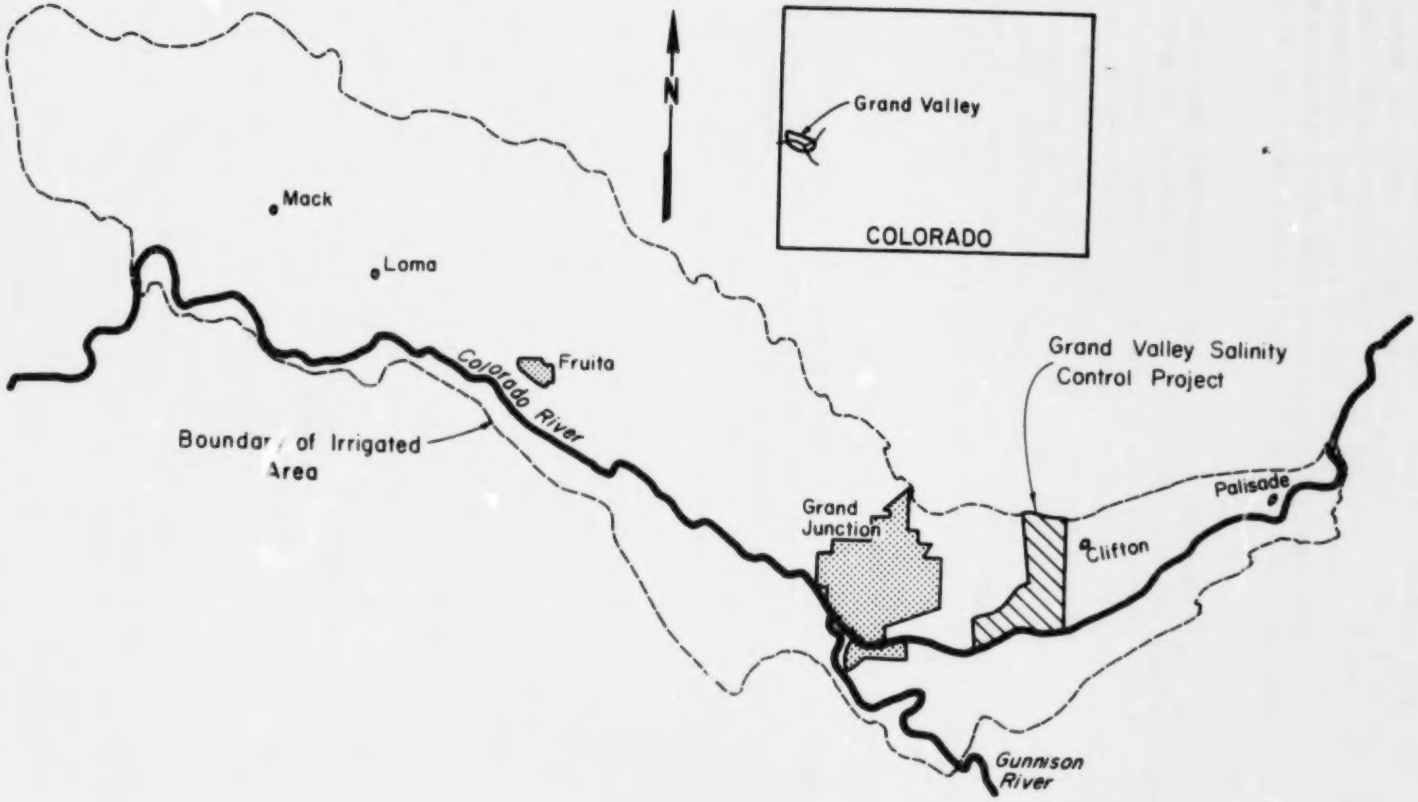
N
Grand Valley
COLORADO
Mack
Loma
Fruita
Colorado River
Boundary of Irrigated Area
Grand Junction
Grand Valley Salinity Control Project
Clifton
Palisade
Gunnison River

Figure 3. Location of Grand Valley Salinity Control Demonstration Project.

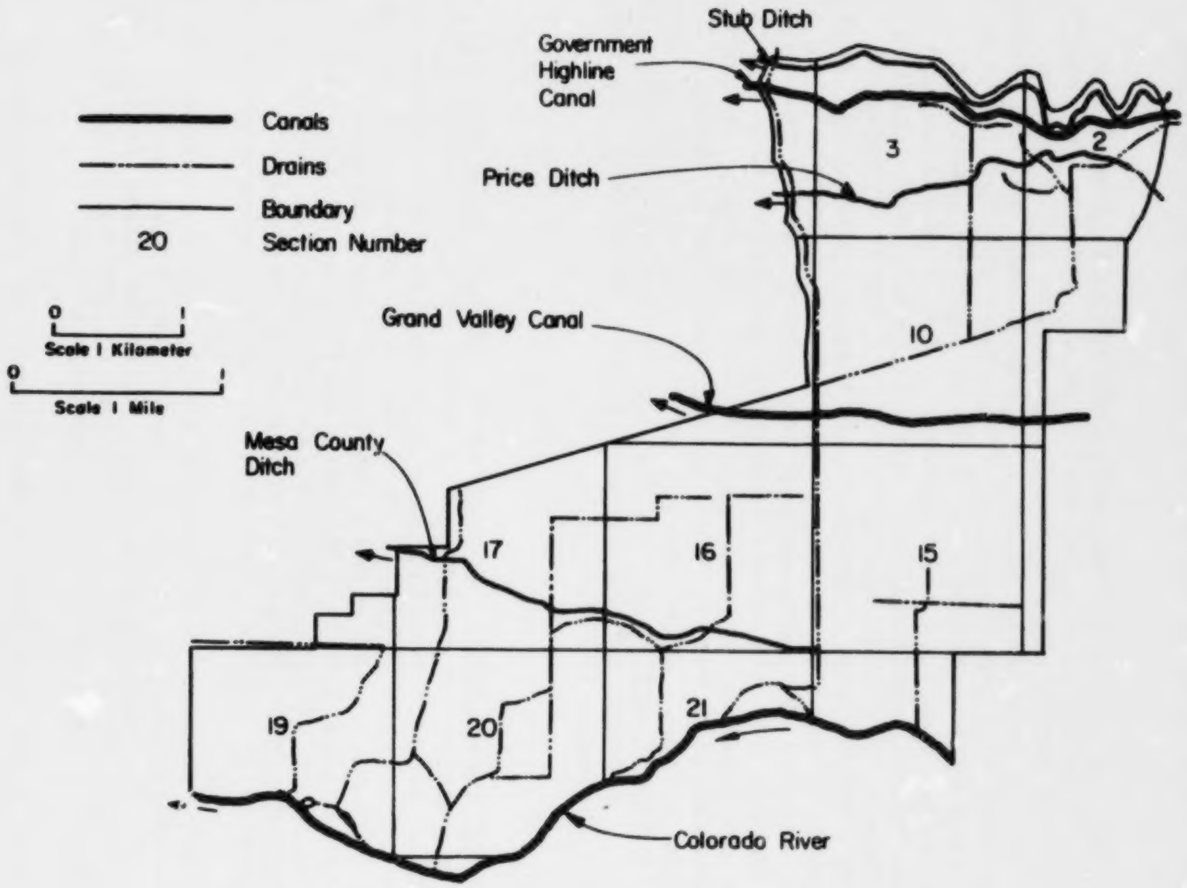
Stub Ditch
Government Highline Canal
Price Ditch
Grand Valley Canal
Mesa County Ditch
Colorado River
Canals
Drains
Boundary
20
Section Number
0
Scale 1 Kilometer
0
Scale 1 Mile
2
3
10
15
16
17
19
20
21

Figure 4. Grand Valley Salinity Control Demonstration Project.

large fraction of the water passing through the local soils returns to the river as deep percolation resulting from overirrigation, measures aimed at improving irrigation efficiencies promise a high potential for controlling salinity. Among all the methods for achieving higher water use efficiencies on the farm, irrigation scheduling is one of the most promising and least expensive.

The results of this demonstration project showed that irrigation scheduling is a necessary tool, but not in itself sufficient for achieving improved irrigation efficiencies. The real strides in reducing the salt pickup caused by overirrigation will come from the employment of irrigation scheduling in conjunction with other improved on-farm irrigation practices. Excessive water supplies, the necessity for rehabilitating the irrigation system (particularly the laterals), and local resistance to change, preclude higher levels of water management during successive irrigations. To overcome these limitations, irrigation scheduling must be accompanied by flow measurement at all the major lateral division points and farm inlets. In addition, it is necessary for the canal companies and irrigation districts to assume an expanded role in delivery of the water, in accepting more responsibility for lateral deliveries, and in changing to a demand type system. More details on this project can be obtained in the EPA Report entitled "Evaluation of Irrigation Scheduling for Salinity Control in the Grand Valley" (Skogerboe, Walker, Taylor and Bennett, 1974b).

Drainage

Part of the initial demonstration project on canal linings included a portion on drainage. A total of $20,000 was spent in this initial project to tile some open drains and concrete slipform some other open drains. This was done to correct two small surface problems in the area. The field data indicated that most of the open drains in the area were performing as intended and were not seeping water back into the groundwater. However, there still existed a need to evaluate the effectiveness of field drainage as a salinity control measure. This was undertaken in 1972.

Drainage studies were not new in the Grand Valley. In fact, drainage investigations in the Grand Valley began shortly after the turn of this century when local orchards began failing due to saline high-water tables. Studies showed the soils to be not only saline but also to have low permeabilities.

At that time, the future development of the Bureau of Reclamation's "Grand Valley Project" loomed as a severe threat to the low lying lands between it and the Colorado River. In answer to the apparent drainage needs, the necessary solutions were clearly set forth but never fully implemented because of the large capital investment required. However, the citizens of

Grand Valley did elect to form a drainage district supported by a mill tax levy in order to construct open ditch drains and some buried tile drains to correct local trouble spots. All of these efforts barely contained the rise in water tables, and today, more than fifty years later, the local conditions remain essentially unchanged.

The construction of open drains has played an important role in the Grand Valley. These drains serve as outlets for the tile interceptor drainage systems. They also intercept and convey tailwater runoff which would otherwise flow over surface lands, infiltrate, and contribute to additional subsurface groundwater flows, subsequently reaching the Colorado River with increased salt pickup.

This study was undertaken with the history of local drainage well in mind, but for different purposes, to skim water from the top of the water table before it reaches chemical equilibrium with the highly saline soils and groundwater in the cobble aquifer, and to demonstrate to local farmers the benefits in increased crop production by improved field drainage resulting in lower soil salinity levels by permitting more effective leaching.

Three farms were selected for field drainage investigations during the 1972 irrigation season. The studies showed that the drainage problems on two of the farms could be alleviated by improved on-farm water management practices, particularly by increasing irrigation efficiency during the early part of the season which would sufficiently reduce deep percolation losses and would keep the groundwater level at a satisfactory depth below the ground surface to allow good crop production.

The field drainage effluent was approximately 3000 mg/l less saline than the concentration of the waters in the cobble aquifer. This significantly demonstrated that the field drainage will "skim" the water before it can reach the higher concentrations. Although it is very expensive ($4225/hectare or $1960/acre), field drainage can be an effective salinity control measure.

In viewing the results of this study, it is obvious that field drainage is a curative rather than preventative measure. High costs of such programs illustrate the need of first minimizing the flows passing through the root zone or seeping from canals and laterals. The smaller amount of water then entering the groundwater could be effectively removed by drainage systems and/or wells located at selected locations. Field drainage as it pertains to objectives of salinity control is a remedy which must be considered but will probably not be implemented as a salinity control measure in the Valley. This project was discussed in much more detail in the EPA Report "Evaluation of Drainage for Salinity Control in Grand Valley" (Skogerboe et al., 1974a).

PURPOSE

The costs of salinity control to sufficiently compensate for future water resource developments in a region like the Colorado River Basin will be high. Savings achieved through the implementation of the most cost-effective alternatives can be substantial. This project was designed to develop and demonstrate cost-effectiveness relationships for salinity control in the Grand Valley of western Colorado.

Economically feasible means of controlling the salinity associated with irrigation return flows had been evaluated individually and independently in previous investigations. In order to extend these results to the formulation of comprehensive plans for controlling salinity on a large scale, it is necessary to describe the interrelationships which exist among the alternatives. Prior to this project some limited evidence had indicated that the functions describing costs and effectiveness of specific salinity control measures were nonlinear. Therefore, if salinity control measures were not mutually exclusive, then an "optimal" salinity control strategy would consist of a combination of several alternatives. The respective composition of such a strategy would depend on the relative magnitude of each hydrologic segment in an irrigated area. Thus, an important step in solving salinity problems was to investigate the nature of improvements incorporating several alternatives, and assessing the impact of a "package" of salinity control measures.

The most significant aspect of this particular demonstration project is the employment of a salinity control technology "package", rather than a single control measure. Experience in the Grand Valley has shown that the most significant progress is made when the gamut of questions can be answered regarding the interrelationships between water management and agricultural production. Thus, the concept of a technology package, along with an understanding of the "system" including other agricultural inputs, provides the necessary base for providing sound advice to the farmer. This in turn facilitates the development of credibility and consequently farmer acceptance.

OBJECTIVES

The primary objective of this demonstration project was to show the advantages of implementing technological improvements within the lateral subsystems, in reducing the salt load entering the Colorado River. As defined in this project, the lateral subsystem begins at the canal turnout and includes all of the water conveyance channels below the turnout and the farm lands served by the lateral water supply. Although major emphasis was upon on-farm improvements, considerable improvements in the water delivery conveyances, improvements in lowering high-water tables (drainage), and tailwater removal improvements were also required.

This project utilized each of the salinity control measures previously evaluated in Grand Valley with the additional use of various irrigation methods to demonstrate on-farm salinity control measures. No single measure (except a desalination plant) will adequately alleviate the salt load from an irrigated area. Demonstrating the complete package of salinity control measures is a "first", which can also be expected to reduce the salt load beyond the sum of each individual measure because of improvements in the operation and management of each lateral.

The objectives of this demonstration project are summarized below:

A. Utilize salinity control technology to demonstrate the complete package of salinity control measures for nine laterals, including a preevaluation and postevaluation of the following control measures:

   1. Utilization of existing canal lining technology developed in the Grand Valley;

   2. Utilization of irrigation scheduling technology presently in use in the Grand Valley;

   3. Evaluation of salinity control benefits resulting from various on-farm irrigation methods as a part of this demonstration project;

   4. Utilization of drainage technology previously evaluated in the Grand Valley; and

   5. Utilization of the concurrent research project, "Irrigation Practices, Return Flow Salinity, and Crop Yields," to predict the chemical quality changes in the Colorado River resulting from this demonstration project.

B. Determine the cost-effectiveness of each salinity control measure, various combinations of salinity control measures, and the complete package of salinity control technology for this demonstration project.

C. Conduct a two-day highly publicized field days.

D. Determine the best practicable salinity control technology for the Grand Valley, including valley-wide cost-effectiveness.

E. Analyze effectiveness of local administrative controls in implementing salinity control technology.

   1. Tailwater runoff control

   2. Permit system
      a. Individual farm
      b. Lateral
      c. Canal (Irrigation Co.)
      d. Entire Valley

   3. Influent standards
      a. Farm inlet
      b. Lateral turnout
      c. Canal diversion

F. Delineate the essential elements of an educational program to transfer this information to other farmers in the Grand Valley, along with farmers in other irrigated areas of the Colorado River Basin.

This report covers only Objective A3. The preceding report, "Implementation of Agricultural Salinity Control Technology in Grand Valley" (Evans et al., 1978) covers all the other objectives except D. The final report of this research program, "Best Management Practices for Salinity Control in Grand Valley" (Walker et al., 1978), is devoted to satisfying Objective D.

RESEARCH APPROACH

The principal study area in the Grand Valley, which has been used for evaluating the effectiveness of canal and lateral lining, irrigation scheduling, and tile drainage in reducing the salt load entering the Colorado River was also used in this demonstration project. The advantage in continuing to utilize this study area is that the hydrology is already known. In addition, there has been considerable expenditure of funds in both equipment and personnel for instrumenting this particular demonstration area. The wealth of available information provides a strong basis for evaluating the effectiveness of salinity control measures.

With all the available knowledge regarding the study area, a lateral including the associated lands served by the lateral water supply can be used as a subsystem for evaluating the salinity reduction in the Colorado River resulting from the implementation of a salinity control technology package.

In order to facilitate the continued participation by the irrigation interests in the Grand Valley, the laterals were selected to cover as many canals as possible. The final selection, as shown in Figure 5, had two laterals under the Highline Canal, one under the Price Ditch, three under the Grand Valley Canal, and three under the Mesa County Ditch. Figure 5 also shows the locations of the previous canal lining, irrigation scheduling and drainage investigations. It should be pointed out that the lands served by the Highline Canal in the demonstration area are served under carriage contract with the Mesa County Irrigation District (Stub Ditch) and the Palisade Irrigation District (Price Ditch). Therefore, all the irrigation entities in the demonstration area are involved directly in the project.

The laterals were selected to capitalize on previous work regarding canal and lateral lining, irrigation scheduling, and drainage studies. The hydrologic knowledge already gained in this demonstration area allows routine surface water and groundwater monitoring to evaluate the overall effectiveness of the salinity control technology package.

The experimental design for the preevaluation was primarily aimed at providing specific information for the 330.7 hectares (817 acres) undergoing treatment listed in Table 1. The field data collection program provided a basis for the design of irrigation and drainage facilities and sufficient data to allow predictions of salinity benefits resulting from each specific salinity control measure. Although the postevaluation included the monitoring of water and salts entering and leaving the demonstration area, the primary emphasis was the on-site evaluation of each specific salinity control measure. The on-site evaluation was then compared with the results of the total demonstration area hydrosalinity monitoring program.

The selection of a lateral as a subsystem, rather than an individual farm, had a tremendous advantage of control at the lateral turnout. In this way, both the quantity of flow and the time of water delivery could be controlled, facilitating improved water management throughout the subsystem.

Considerable experience has been gained in improving and "tuning up" the existing irrigation methods while evaluating irrigation scheduling as a salinity control measure in the Grand Valley. In addition, more advanced irrigation methods have been evaluated as to salinity benefits in the Grand Valley. The irrigation systems constructed under this project included automated farm head ditches, sprinkler irrigation, and trickle irrigation.

A two-day "Field Days" was conducted during the third year of this project in the month of August. This event was primarily directed towards the growers in the Grand Valley and secondly to irrigation leaders (mostly growers) throughout the Upper Colorado River Basin. Some State and Federal agency personnel also attended. This was coupled with an irrigation equipment show

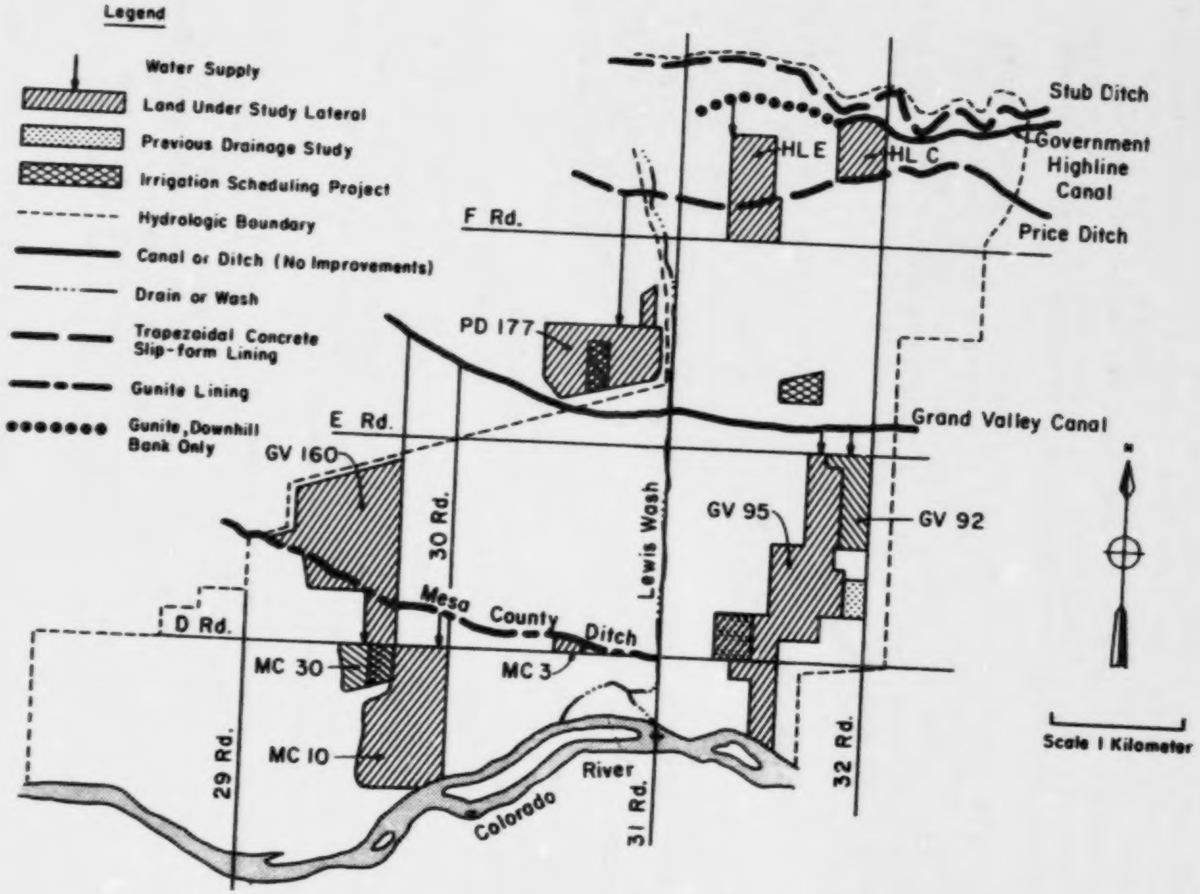
Legend
Water Supply
Land Under Study Lateral
Previous Drainage Study
Irrigation Scheduling Project
Hydrologic Boundary
Canal or Ditch (No Improvements)
Drain or Wash
Trapezoidal Concrete Slip-form Lining
Gunite Lining
Gunite, Downhill Bank Only
Stub Ditch
HL E
HL C
Government Highline Canal
Price Ditch
F Rd.
PD 177
Grand Valley Canal
E Rd.
GV 160
30 Rd.
Lewis Wash
GV 95
GV 92
N
Mesa County Ditch
D Rd.
MC 30
MC 3
MC 10
29 Rd.
Colorado River
31 Rd.
32 Rd.
Scale 1 Kilometer

Figure 5. Map showing the location of the nine selected lateral subsystems incorporated in the project, and the locations of the previous canal linings, irrigation scheduling and drainage investigations.

TABLE 1. FINAL SELECTION OF LATERALS INCLUDED IN PROJECT

Lateral Identification	Canal	Area		No. of Irrigators[5]
		Hectares	Acres	
HL C	Highline Canal	13.1	32.4	1
HL E[1]	Highline Canal	35.9	88.6	2
PD 177[1] [4]	Price Ditch	27.8	68.8	6
GV 92	Grand Valley Canal	24.3	59.9	6
GV 95 [2] [3]	Grand Valley Canal	79.1	195.7	13
GV 160	Grand Valley Canal	78.7	194.3	8
MC 3	Mesa County Ditch	3.7	9.0	1
MC 10[1]	Mesa County Ditch	54.0	133.4	9
MC 30[2]	Mesa County Ditch	14.1	34.7	1
	TOTAL	330.7	816.8	47

1/ These laterals were part of the earlier EPA funded canal and lateral lining study.

2/ This lateral was part of the earlier EPA funded field drainage study.

3/ This lateral consolidated an additional 70 acres from two other laterals.

4/ A portion of this lateral was included in the previous EPA funded irrigation scheduling program.

5/ An irrigator is defined as a person who farms more than one acre. In actuality, 89 persons are involved in the operation of this project.

and was cosponsored by the Colorado State University Cooperative Extension Service.

The concurrent EPA research project, "Irrigation Practices, Return Flow Salinity, and Crop Yields," which was also conducted in the Grand Valley, provided necessary input for developing the cost-effectiveness of each salinity control measure. In addition, the results from this same project provided valuable information regarding increased crop yields that can be expected from improved water management practices. The combined results of this research project and the demonstration project are extremely important in establishing the benefits to be derived from implementing a salinity control technology package. The detailed results of this project can be found in the EPA reports entitled, "Irrigation Practices and Return Flow Salinity in Grand Valley" (Skogerboe et al., 1978b) and "Potential Effects of Irrigation Practices on Crop Yields in Grand Valley" (Skogerboe et al., 1978a). The combined results of the two projects are incorporated in the EPA report "Best Management Practices for Salinity Control in Grand Valley."

Although each irrigated area is somewhat different, the knowledge already gained in the Grand Valley can be utilized in conjunction with existing and secondary sources of data for other areas, particularly irrigated areas in the Upper Colorado River Basin, to formulate plans and priorities for implementing salinity control technology in such areas.

SECTION 2

CONCLUSIONS

The cost-effectiveness associated with each salinity control alternative is the basis for determining the formulation of an implementation policy. Studies reported in the technical literature indicate that the salinity damages in the Lower Colorado River Basin range from $150 to $350 (Section 12) per metric ton per year when extended to the Grand Valley. Local benefits to the project such as increased crop yields, reduced irrigation system maintenance costs, increased land values and other factors were not evaluated as part of this report and are not included in the cost-effectiveness of the various alternatives. The evaluation of the salinity control benefits resulting from various on-farm irrigation methods yielded the following conclusions:

1) Evaluation of alternative methods of irrigation implies that cropland evapotranspiration can be well estimated. Three empirical approaches were used in this study: (a) the Blaney-Criddle method; (b) the Jensen-Haise method; and (c) the Modified Penman method. The Blaney-Criddle approach underestimated lysimeter data by about 40 percent on a seasonal basis; corrections in the temperature coefficient reduced this seasonal error to zero, but estimates were still substantially in error for weekly time periods. The Jensen-Haise approach overestimated seasonal evapotranspiration by approximately 5 percent with a 10-15 percent error during the early spring windy periods. The Penman approach was better than the Jensen-Haise method in estimating seasonal values, but was not better at approximating the seasonal distribution of evapotranspiration.

2) Irrigation scheduling by itself is not a significant salinity control alternative, but should be part of any strategy for improved water management in order to maximize the effectiveness of physical improvements.

3) Irrigation scheduling should be referenced to the areas of a field receiving the least amounts of water, and then related to the operation of the irrigation system so that the duration of a water application is equal to

the time required to refill the "least watered" root zone areas. In sprinkler irrigation, the least watered or "critical" areas would be the diagonal distance between two sprinklers on adjacent laterals; whereas for surface irrigated systems, it is at the lower end of the field.

4) Furrow irrigation is the predominant method of water application in the Grand Valley. Existing application efficiencies [(available root zone storage/applied water) x 100] is about 64 percent. Strict adherence to the scheduling philosophy outlined in (3) above would result in application efficiencies of 85 to 90 percent, but this appears to be unrealistic without substantial investments in automation. The cut-back method of furrow irrigation was demonstrated in the Valley at about the same cost-effectiveness for controlling salinity as head ditch linings.

5) Border irrigation is applicable in the Grand Valley, but not presently accepted. Graded borders have approximately the same potential application efficiency as furrow irrigation, while the costs would be higher due to higher land leveling requirements. In addition, border irrigation requires more skilled labor and a higher degree of management than is presently available in the area.

6) Level borders offer a large potential for reducing salt loading if problems with soil crusting can be controlled. Also, the level borders require a very high level of management capability, and would be quite adaptable to automation.

7) Properly managed sprinkler systems offer a large potential for reducing salt loading from irrigation return flows. Solid-set systems are not presently cost-effective in the Grand Valley, whereas the less expensive moveable systems (side-roll, etc.) are very competitive in an on-farm salinity reduction program. Achievable application efficiencies for sprinkler irrigation are 85 to 95 percent depending on the management of the system.

8) Trickle irrigation is cost-effective for orchard crops and has the greatest potential for reducing return flow salinity from these areas. However, it can be applied to less than 10 percent of the Valley. Due to the large cost of these systems, trickler irrigation has a much poorer cost-effectiveness than properly managed surface irrigation systems.

9) Since sprinkler and trickler irrigation methods are not controlled by soil properties, changing to these systems potentially would have a very large impact on reducing the salt loading from the early season irrigations. These early irrigations are responsible for more than 50 percent of the total annual salt load for irrigation return flows in the Grand Valley.

10) A comparison of the cost-effectiveness relationships of the various irrigation system improvements indicates that head ditch linings, gated pipe, and/or automated cutback furrow irrigation will reduce salinity for approximately \$100-\$110 per metric ton per year (i.e., one ton of salt will be eliminated from the Colorado River each year over the life of the improvement at an initial investment of \$100-\$110 for the first year's ton). A limit of 146,500 metric tons per year is amenable to this alternative. Sprinkler irrigation could be utilized to extend local salinity control to 171,000 metric tons per year, at a cost of more than \$130 per ton. The maximum control would be achieved through massive conversion to trickle irrigation (227,000 metric tons per year) at a cost of about \$200 per ton.

11) Comparison of on-farm salinity control methods on a cost-effectiveness basis in the Grand Valley indicates that these measures are second only to lateral linings in feasibility.

12) Installation of potentially efficient irrigation systems will not by itself reduce salt loading from irrigation return flows. These systems must be properly managed to realize any improvement over existing conditions in the Grand Valley. Likewise, much more efficient management and control of existing irrigation systems in the Grand Valley would result in significant salt load reductions. For this reason, successful implementation requires large-scale extension type programs to provide necessary technical assistance and a strong interaction with farmers.

SECTION 3

RECOMMENDATIONS

As a result of this research project, there are several recommendations which can be made concerning the implementation of a "total" salinity control program and the evaluation of salinity control benefits resulting from various on-farm irrigation methods.

1) The lateral improvement program and the on-farm program should not be two separate programs, but a single program which plans, constructs, and operates a combination of improvements moving from one lateral to the next.

2) An effective plan of physical improvements must be developed which will result in improved water management for increasing agricultural productivity in the Grand Valley, while reducing the salt load in the Colorado River.

3) Irrigation scheduling in the Grand Valley should be included in any plan to implement on-farm irrigation system improvements for salinity control. The primary objective should be to develop operational criteria for determining the length of each irrigation set and flow rates which just meets the root zone storage requirements in the least watered areas of a field. Irrigators should be advised of the time water should be applied to their fields for a range of days over which the fields might be irrigated. Predicting the exact dates of subsequent irrigations should be of secondary importance.

4) Existing salinity control plans should be reevaluated in terms of the on-farm potential. Reducing field head ditch seepage with slip form concrete lining or gated pipe should be considered a salinity control alternative second only to lateral linings in importance. Automated cut-back furrow irrigation should be considered as equal in cost-effectiveness with simple head ditch linings, but it has a higher potential for total salt load reduction.

5) Sprinkler and trickle irrigation should be considered when the control of on-farm salinity is to be reduced as much as possible. However, the marginal costs of these possible improvements exceed the costs of lining the Government Highline Canal. Therefore, the level of on-farm improvements needs to be evaluated in terms of other alternatives.

6) The relative impact of on-farm improvement in reducing the salinity of the Colorado River ought to be considered throughout the Basin before plans are finalized for the Grand Valley. In other words, on-farm improvements in the Grand Valley coupled with similar programs in other areas may be more cost-effective than complete off-farm full scale improvement programs (canal lining, desalting, drainage, etc.) in the Grand Valley.

7) The ultimate level of salinity control decided upon for the Grand Valley should be evaluated on a basinwide context. The marginal costs of salinity control are linearly distributed and, therefore, other areas will be better sites for salinity control efforts than plans approaching full-scale control in the Grand Valley. Consequently, the Grand Valley studies of on-farm improvements should be extended at least in a general sense to other irrigated areas in the Upper Colorado River Basin.

8) The plan of improvement must include sufficient flow measurement structures throughout the lateral subsystem to facilitate equitable distribution of the water supplies and improved irrigation practices.

9) Adequate numbers of technical assistance personnel should be available to help the irrigators develop proficiency with their system and develop a higher level of water management.

10) Given the levels of technical assistance personnel needed to work with farmers, and the current shortage of trained manpower with on-farm water management experience, special training courses should be developed.

11) Once the physical facilities are complete, a program of "scientific" irrigation scheduling should be used to maximize the effectiveness of the physical improvements.

12) The success of any salinity control program rests finally with the degree of participation by the farmers themselves. Farmers who have made exceptional progress

in improving their on-farm water management practices should be given special recognition.

13) The implementation program should be monitored, evaluated, and continuously refined. This process will not only maximize the effectiveness of the Grand Valley Salinity Control Program, but will provide valuable information and experience for implementing irrigation return flow quality control programs in other areas of the West.

SECTION 4

THE GRAND VALLEY

LOCATION

The Grand Valley is located in west central Colorado near the western edge of Mesa County. Grand Junction, the largest city in Colorado west of the Continental Divide, is the population center of the Valley. The area was illustrated in Figure 3.

The Grand Valley is a crescent shaped area which encompasses about 49,800 hectares (123,000 acres) of which 57.7 percent or about 28,650 hectares (70,800 acres) are irrigated. Urban and industrial expansion, service roads and farmsteads, idle and abandoned lands account for most of the land not farmed. The Valley was carved in the Mancos Shale formation (a high salt-bearing marine shale) by the Colorado River and its tributaries. The Colorado River enters the Grand Valley from the east, is joined by the Gunnison River at Grand Junction and then exits to the west.

Spectacular and colorful canyons flank the southwestern edge of the Valley (Colorado National Monument). A steep escarpment known as the Book Cliffs (which are the southern edge of the Roan Plateau) rises from the Valley floor on the north; the 3,050 meter (10,000 foot) high Grand Mesa lies to the north and east, and distantly to the southeast the San Juan Mountains can be seen; to the south and west lie the rough, steep deeply eroded hilly lands of the high terraces or mesas of the canyonlands of the Colorado Plateau.

Within the Grand Valley, the irrigated lands have developed on geologically recent alluvial plains consisting of broad coalescing alluvial fans and on older alluvial fans, terraces and mesas. Included in the Valley lands are stream flood plains and various rough lands occurring as terraces, escarpments, high knobs, and remnants of former mesas.

POPULATION

The majority of the population of Mesa County reside in the Grand Valley near and within the city limits of Grand Junction.

In 1970 the population of the city of Grand Junction was 20,170, which is 37 percent of the total Mesa County population. The population has been growing steadily during the past decades, and the 1974 estimated population of Grand Junction was 27,000 while that of Mesa County was nearly 62,000. The projected 1990 population of Mesa County is 90,000.

Grand Junction is a regional trade and service center for the considerable agricultural and mining interests in western Colorado, northwestern New Mexico, northeast Arizona and eastern Utah because of its access to major highways, rail, and airline systems. During the 1950's, the area became and still is the center of the uranium exploration boom and several uranium development projects sponsored by the government. Recent program expansions related to energy have caused an economic upswing for the area. At the present time, the Grand Valley is a focal supply point for the budding oil shale and sodium bicarbonate (Nahcolite) industries which lie to the north and west. The area is also a supply and service center for a considerable oil and natural gas drilling and exploration industry.

CLIMATE

The Grand Valley area enjoys a moderate year-around climate which is influenced more by the mountain ranges in the Upper Colorado River Basin than by the latitude. The movement of air masses is affected by the mountain ranges so that the high elevations are relatively wet and cool, whereas the low plateaus and valleys are much drier and subject to wide temperature ranges. The characteristic climate in the lower altitudes is hot and dry summers and cool winters.

The Grand Valley has a climate common to all of the semi-arid Colorado River Basin. Most of the precipitation to the Valley is provided from the Pacific Ocean and the Gulf of Mexico, whose respective shores are 1,200 and 1,800 kilometers (750 and 1,100 miles) away. During the period from October to April, Pacific moisture is predominant, but the late spring and summer months receive moisture from the Gulf of Mexico. The advancing air masses are forced to high altitudes and lose much of their moisture either before entering the area (Gulf of Mexico fronts) or after leaving the area (Pacific fronts).

The Grand Valley receives an average annual precipitation of only 211 mm (8.29 inches) and practically all the irrigation and potable water supplies come from the nearby high mountain snowpacks. The monthly distribution of precipitation and temperature for Grand Junction is shown in Figure 6. The climate is marked by a wide seasonal range, but sudden or severe weather changes are infrequent due primarily to the high ring of mountains around the Valley.

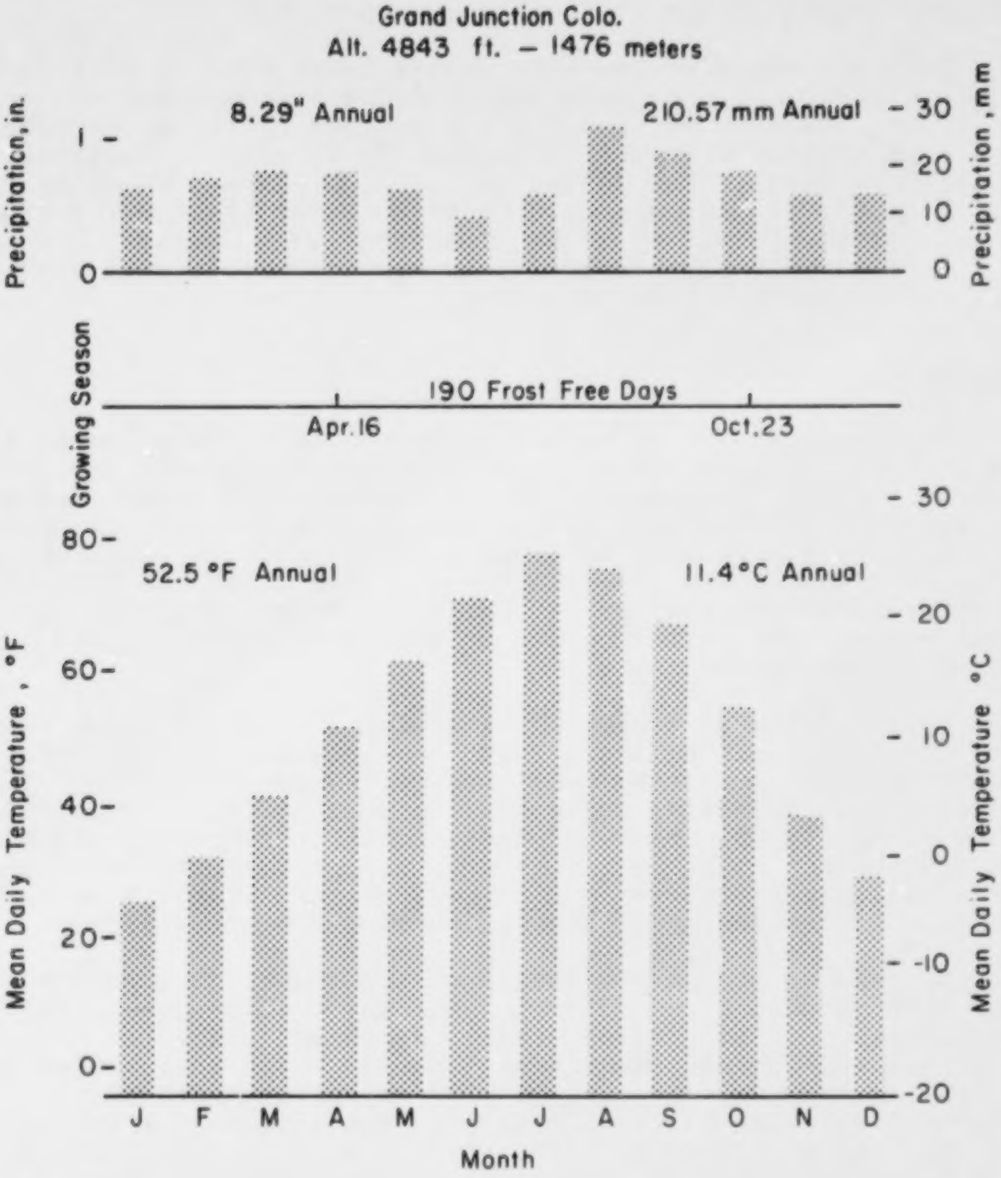

Figure 6. Normal precipitation and temperature at Grand Junction, Colorado (U.S. Department of Commerce, 1968).

The usual occurrence of precipitation in the winter is snow and during the growing season is in the form of light showers from thunderstorms. Severe cloudbursts occur infrequently during the late summer months and hail storms are rare.

Although temperatures have ranged to as high as 40.6 degrees C (105 degrees F), the usual summer temperatures range to the middle and low 30's degrees C (90's degrees F) in the daytime and around 15 degrees C (low 60's degrees F) at night. Relative humidity is usually low during the growing season, which is common in all of the semi-arid Colorado River Basin. The average annual relative humidity is 58.8 percent. The prevailing wind direction is east-southeast with an average velocity of about 13.4 kilometers per hour (8.3 mph).

GEOLOGY

The plateaus and mountains in the Colorado River Basin are the products of a series of land masses deeply eroded by wind and water. However, long before the earth movements which created the uplifted land masses, the region was the scene of alternate encroachment and retreat of great inland seas. The sediment rock formations underlying large portions of the basin are the result of material accumulated at the bottom of these seas. In the Grand Valley, the primary geologic formation resulting from this action is the Mancos Shale.

Mancos Shale is a very thick sequence of drab, gray, fissle, late Cretaceous marine shale that lies between the underlying Dakota sandstones and the overlying Mesa Verde formation. The thickness of the Mancos Shale usually varies from between 900 to 1,500 meters (3,000 and 5,000 feet). Due to its great thickness and its ability to be easily eroded, this shale forms most of the large valleys of western Colorado and eastern Utah. A general geologic cross-section of the Valley can be seen in Figure 7.

Because of the marine origin of the shale, it contains a very high percentage of water soluble salts which can be readily seen in the many patches of alkali (white and black) in both irrigated and nonirrigated areas. The types of salts which are present in the shale are mostly calcium sulfate with small amounts of sodium chloride, sodium sulfate, magnesium sulfate, and calcium and magnesium carbonates. In fact, the minerals gypsum and calcite (calcium sulfates) are commonly found in crystaline form in open joints and fractures of the Mancos Shale, as well as in the soil profile.

Due to the compactness of the clay and silt particles making up the shale, the formation is not considered water-bearing at depth. However, the weathered zone near the surface does transmit small quantities of water along joints, fractures, and

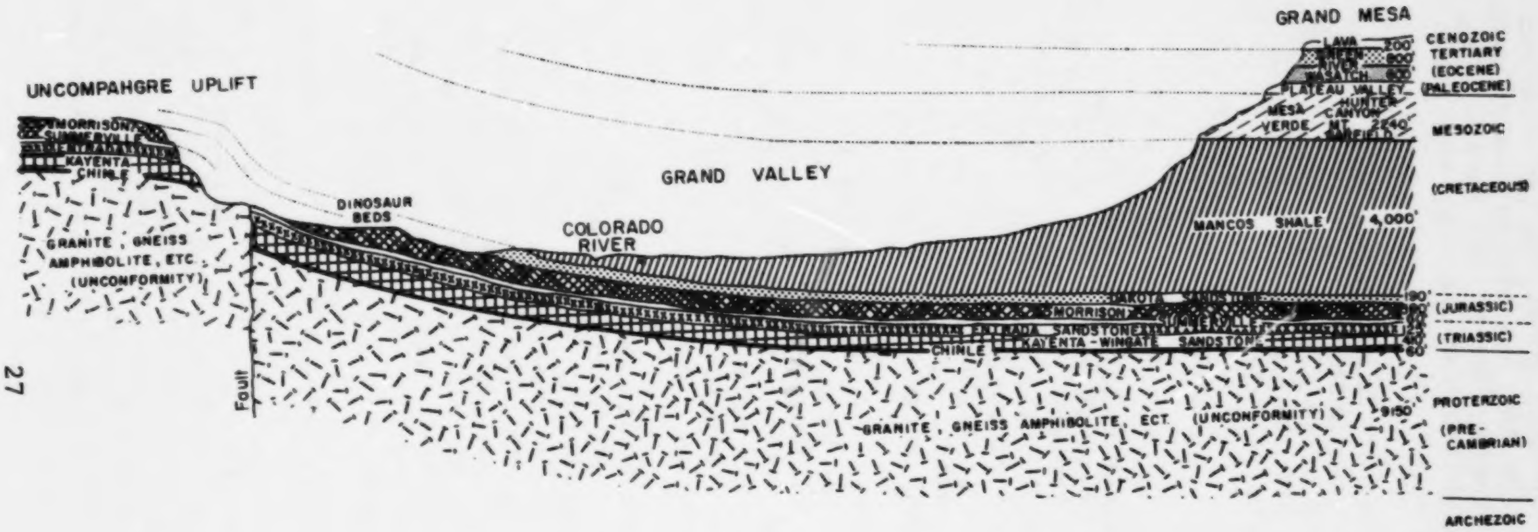
UNCOMPAHGRE UPLIFT
MORRISON
SUMMERVILLE
KAYENTA
CHINLE
GRANITE, GNEISS
AMPHIBOLITE, ETC.
(UNCOMFORMITY)
Fault
DINOSAUR BEDS
COLORADO RIVER
GRAND VALLEY
GRAND MESA
LAVA
200'
GREEN RIVER
800'
WASATCH
600'
PLATEAU VALLEY
MESA VERDE
HUNTER CANYON
MT. GARFIELD
2240'
MANCOS SHALE
4,000'
DAKOTA
190'
MORRISON
SUMMERVILLE
ENTRADA SANDSTONE
KAYENTA - WINGATE SANDSTONE
CHINLE
60'
GRANITE, GNEISS AMPHIBOLITE, ECT.
(UNCONFORMITY)
9150'
CENOZOIC
TERTIARY
(EOCENE)
(PALEOCENE)
MESOZOIC
(CRETACEOUS)
(JURASSIC)
(TRIASSIC)
PROTERZOIC
(PRE-CAMBRIAN)
ARCHEZOIC

Figure 7. General geologic cross section of the Grand Valley (USDA, 1955).

open bedding planes. In this zone, the percolating water, which primarily originates from the overirrigation of cropland, dissolves the salts directly out of the shale. The soils of the Valley are also quite saline because they have been derived from the Mancos Shale.

A gravel and cobble layer has been found under some parts of the irrigated areas in the Grand Valley. It is believed to be ancient stream deposits of the Colorado River, laid down in recent geologic time, and serves as an aquifer for transmitting highly saline groundwater to the river.

SOILS

The physical features describing the project area are similar to the entire Grand Valley. The soils in the Valley were classified by the Soil Conservation Service (SCS) in cooperation with the Colorado Agricultural Experiment Station in 1955. Using these data, a soil classification map of the Grand Valley's irrigated area is shown in Figure 8. The soil classification symbols, along with a general description of each symbol and the relative percent of areal extent, are tabulated in Table 2.

The dry desert climate of the area has restricted the growth of natural vegetation, and because of the lack of organic matter, the soils are very low in nitrogen content. The natural inorganic content is high in lime carbonate, gypsum, sodium, potassium, magnesium and other calcium salts. With the addition of irrigation, some locations have experienced high salt concentrations with a resulting decrease in crop productivity.

Although natural phosphate exists in the soils, it becomes available too slowly for use by cultivated crops, and fertilizer applications greatly aid yields. Other minor elements such as iron are generally available for most crops except in those areas where drainage is inadequate. The soils in the area are of relatively recent origin, and consequently, they contain no definite concentration of lime or clay in the subsoil horizons as would be expected in weathered soils. Some areas in the Valley have limited farming use because of poor internal drainage, which results in waterlogging and salt accumulations.

Lying on top of the Mancos Shale and below the alluvial soils is a large cobble aquifer extending north from the river to about midway up the irrigated area for most of the length of the Valley. The approximate areal extent of this aquifer can be seen in Figure 9. The importance of this aquifer with respect to the drainage problems of the area has been demonstrated by a cooperative study in 1951 between the Colorado Experiment Station in conjunction with the United States Department of Agriculture, Agricultural Research Service (USDA-ARS) which evaluated the

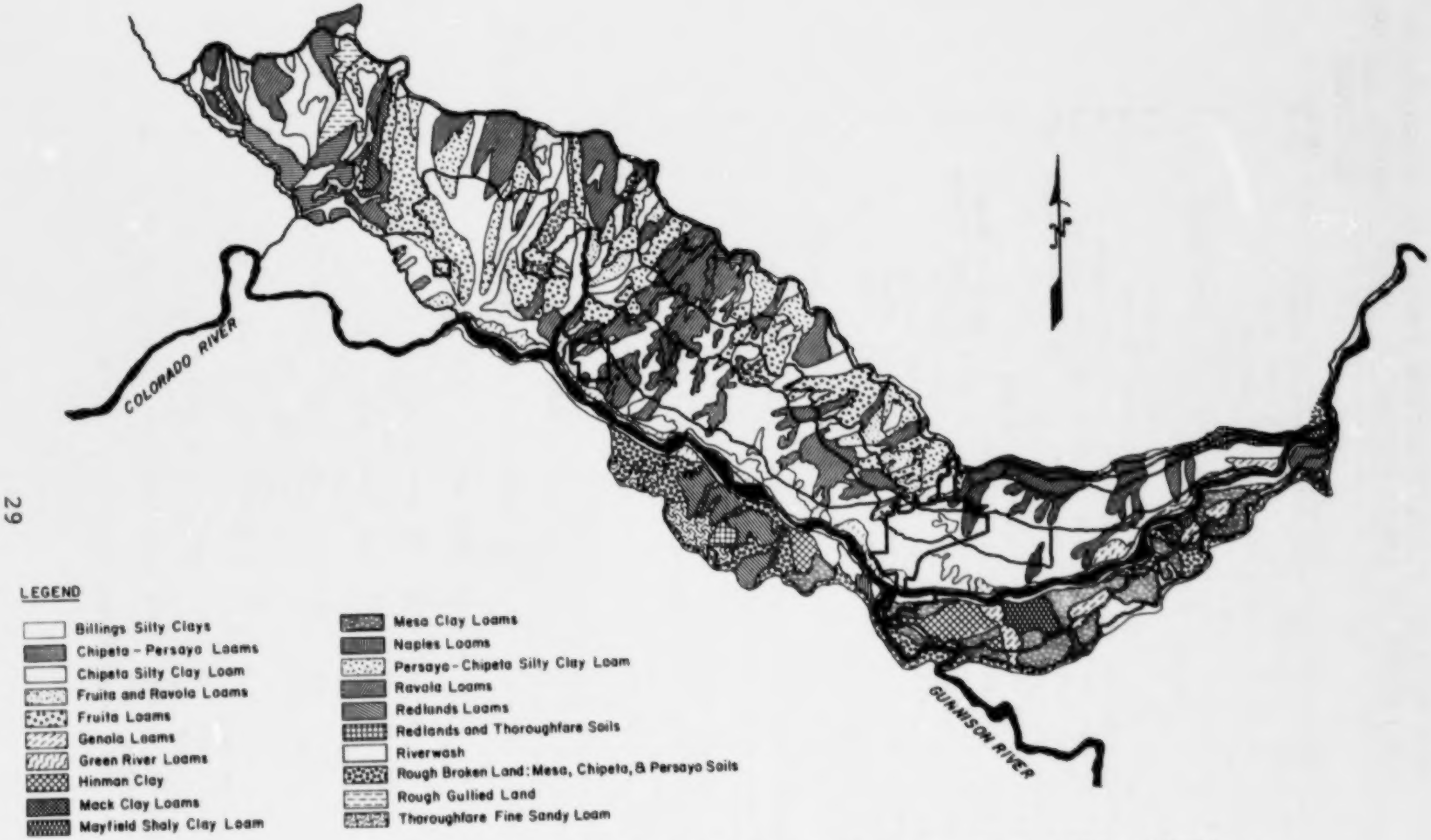
COLORADO RIVER
GUNNISON RIVER
N
LEGEND
Billings Silty Clays
Chipeta - Persayo Loams
Chipeta Silty Clay Loam
Fruita and Ravola Loams
Fruita Loams
Genola Loams
Green River Loams
Hinman Clay
Mack Clay Loams
Mayfield Shaly Clay Loam
Mesa Clay Loams
Naples Loams
Persayo - Chipeta Silty Clay Loam
Ravola Loams
Redlands Loams
Redlands and Thoroughfare Soils
Riverwash
Rough Broken Land: Mesa, Chipeta, & Persayo Soils
Rough Gullied Land
Thoroughfare Fine Sandy Loam

Figure 8. Soils map of irrigated lands in Grand Valley (from USDA, 1955).

TABLE 2. SOIL MAPPING CLASSIFICATION INDEX AND APPROXIMATE PERCENTAGE OF AREAL EXTENT IN GRAND VALLEY, COLORADO

Map Symbol	Soil Type	Approximate Percent
Bc	Billings silty clay loam, 0 to 2 percent slopes	25.4
Bd	Billings silty clay loam, 2 to 5 percent slopes	.6
Ba	Billings silty clay, 0 to 2 percent slopes	2.7
Bb	Billings silty clay, 2 to 5 percent slopes	.1
Be	Billings silty clay, moderately deep over Green River soil material, 0 to 2 percent slopes	.7
Cd	Chipeta silty clay loam, 0 to 2 percent slopes	2.4
Ce	Chipeta silty clay loam, 2 to 5 percent slopes	2.8
Ca	Chipeta-Persayo shaly loams, 2 to 5 percent slopes	.8
Cb	Chipeta-Persayo shaly loams, 5 to 10 percent slopes	1.9
Cc	Chipeta-Persayo silty clay loams, 5 to 10 percent slopes	1.5
Fe	Fruita clay loam, 0 to 2 percent slopes	2.2
Ff	Fruita clay loam, 2 to 5 percent slopes	.4
Fg	Fruita clay loam, moderately deep, 0 to 2 percent slopes	.6
Fl	Fruita clay loam, moderately deep, 2 to 5 percent slopes	1.1
Fi	Fruita gravelly clay loam, 2 to 5 percent slopes	.6
Fk	Fruita gravelly clay loam, 0 to 2 percent slopes	.1
Fm	Fruita gravelly clay loam, 5 to 10 percent slopes	.1
Fn	Fruita gravelly clay loam, moderately deep, 2 to 5 percent slopes	.5
Fo	Fruita gravelly clay loam, moderately deep, 5 to 10 percent slopes	.1
Fp	Fruita very fine sandy loam, 0 to 2 percent slopes	1.1
Fr	Fruita very fine sandy loam, 2 to 5 percent slopes	.5
Fs	Fruita very fine sandy loam, moderately deep, 0 to 2 percent slopes	.5
Ft	Fruita very fine sandy loam, moderately deep, 2 to 5 percent slopes	1.0
Fu	Fruita very fine sandy loam, moderately deep, 5 to 10 percent slopes	.1
Fc	Fruita and Ravola loams, 2 to 5 percent slopes	1.2
Fd	Fruita and Ravola loams, moderately deep, 2 to 5 percent slopes	.3
Fa	Fruita and Ravola gravelly loams, 5 to 10 percent slopes	.7
Fb	Fruita and Ravola gravelly loams, 20 to 40 percent slopes	.1
Ga	Genola clay loam, 0 to 2 percent slopes	.2
Gb	Genola clay loam, 2 to 5 percent slopes	1
Gc	Genola clay loam, deep over Hinman clay, 0 to 2 percent slopes	.5
Gd	Genola fine sandy loam, deep over gravel, 0 to 2 percent slopes	1
Gf	Genola loam, 2 to 5 percent slopes	.2
Gg	Genola very fine sandy loam, deep over gravel, 0 to 2 percent slopes	.1
Gh	Green River clay loam, deep over gravel, 0 to 2 percent slopes	.1
Gk	Green River fine sandy loam, deep over gravel, 0 to 2 percent slopes	.4

(Table 2 continued on following page)

TABLE 2 (Continued).

Map Symbol	Soil Type	Approximate Percent
Gl	Green River silty clay loam, deep over gravel, 0 to 2 percent slopes	.2
Gm	Green River very fine sandy loam, deep over gravel, 0 to 2 percent slopes	1.7
Ha	Hinman clay, 0 to 1 percent slopes	.5
Hb	Hinman clay loam, 0 to 2 percent slopes	1.7
Hc	Hinman clay loam, 2 to 5 percent slopes	.3
Ma	Mack clay loam, 0 to 2 percent slopes	.5
Mb	Mayfield shaly clay loam, 2 to 5 percent slopes	.5
Mc	Mesa clay loam, 0 to 2 percent slopes	1.7
Md	Mesa clay loam, 2 to 5 percent slopes	1.8
Me	Mesa gravelly clay loam, 2 to 5 percent slopes	1.3
Mf	Mesa gravelly clay loam, 5 to 10 percent slopes	.7
Mg	Mesa gravelly clay loam, moderately deep, 2 to 5 percent slopes	.1
Mh	Mesa gravelly clay loam, moderately deep, 5 to 10 percent slopes	.4
Na	Naples clay loam, 0 to 2 percent slopes	.1
Nb	Naples fine sandy loam, 0 to 2 percent slopes	.1
Nc	Navajo silty clay, 0 to 2 percent slopes	.1
Pa	Persayo-Chipeta silty clay loams, 0 to 2 percent slopes	3.4
Pb	Persayo-Chipeta silty clay loams, 2 to 5 percent slopes	2.5
Ra	Ravola clay loam, 0 to 2 percent slopes	6.1
Rb	Ravola clay loam, 2 to 5 percent slopes	.4
Rf	Ravola very fine sandy loam, 0 to 2 percent slopes	4.7
Rg	Ravola very fine sandy loam, 2 to 5 percent slopes	.1
Rc	Ravola fine sandy loam, 0 to 2 percent slopes	2.1
Rd	Ravola fine sandy loam, 2 to 5 percent slopes	.1
Re	Ravola loam, 0 to 2 percent slopes	2.1
Rk	Redlands loam, 2 to 5 percent slopes	.8
Rh	Redlands loam, 0 to 2 percent slopes	[1]
Rl	Redlands loam, 5 to 10 percent slopes	.1
Rn	Redlands and Thoroughfare soils, shallow over bedrock, 5 to 10 percent slopes	.4
Rm	Redlands and Thoroughfare soils, shallow over bedrock, 2 to 5 percent slopes	[1]
Ro	Riverwash, 0 to 2 percent slopes	2.9
Rr	Rough broken land, Mesa, Chipeta, and Persayo soil materials	3.6
Rp	Rough broken land, Chipeta and Persayo soil materials	2.9
Rs	Rough gullied land	2.9
Tb	Thoroughfare fine sandy loam, 2 to 5 percent slopes	1.4
Ta	Thoroughfare fine sandy loam, 0 to 2 percent slopes	.1
Tc	Thoroughfare fine sandy loam, 5 to 10 percent slopes	.1

[1] Less than 0.1 percent.

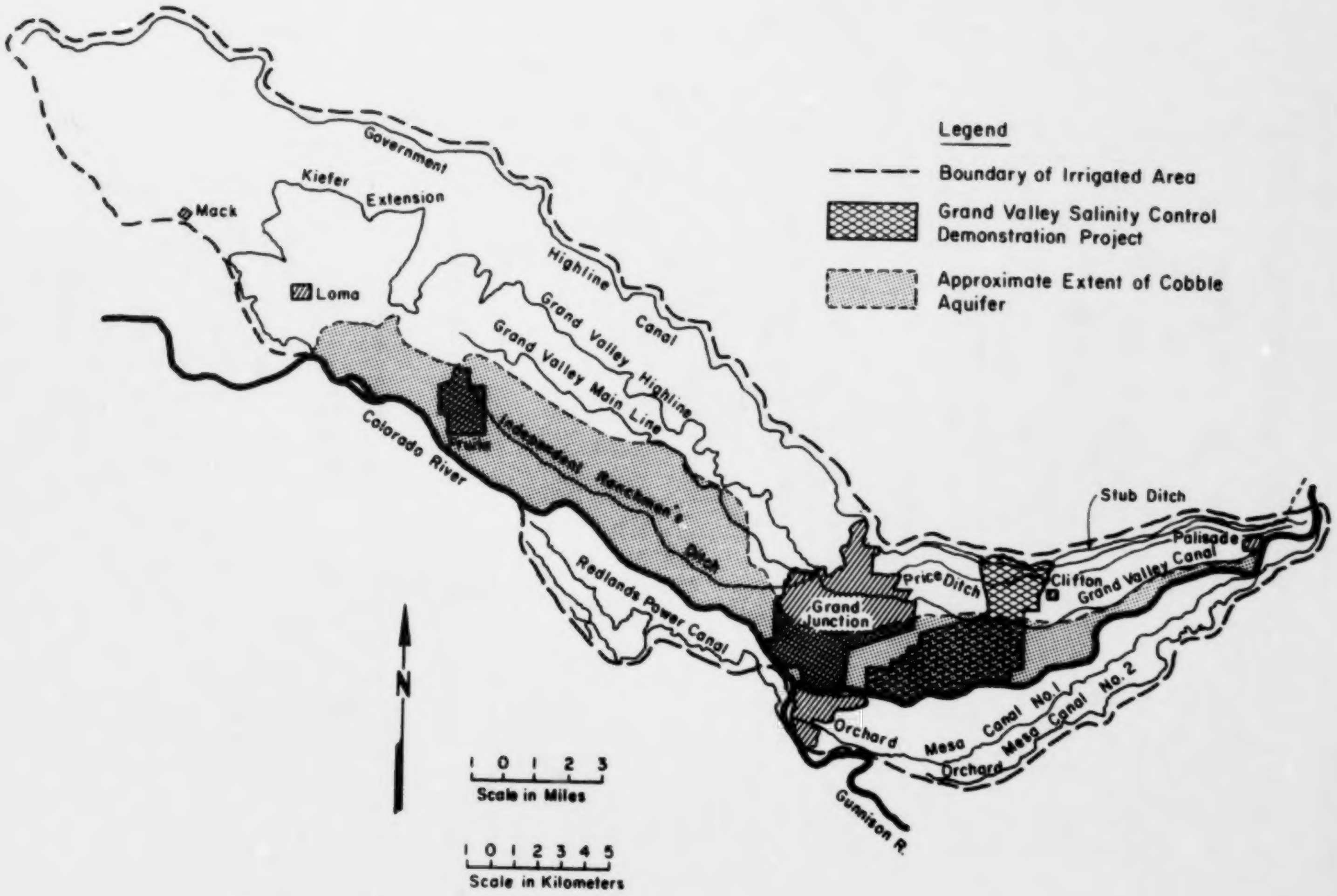
Legend
Boundary of Irrigated Area
Grand Valley Salinity Control Demonstration Project
Approximate Extent of Cobble Aquifer
Mack
Loma
Government
Kiefer
Extension
Highline
Canal
Grand Valley Highline
Grand Valley Main Line
Independent Ranchman's Ditch
Fruita
Colorado River
Redlands Power Canal
Grand Junction
Price Ditch
Stub Ditch
Clifton
Palisade
Grand Valley Canal
Orchard Mesa Canal No. 1
Orchard Mesa Canal No. 2
Gunnison R.
N
0 1 2 3
Scale in Miles
0 1 2 3 4 5
Scale in Kilometers

Figure 9. Approximate areal extent of cobble aquifer in the Grand Valley.

feasiblity of pump drainage from the aquifer. Much of this cobble aquifer is covered with a thin, tight and often discontinuous clay layer and/or a shale gravel washed from the nearby Book Cliffs.

AGRICULTURAL ECONOMIC CONDITIONS

The modification of the Colorado River's flows have yielded benefits in the form of irrigation, power generation, recreation, industrial and domestic water supply, transportation and waste disposal. In recent years, manufacturing and service industries have experienced rapid growth, surpassing mining and agriculture in economic importance in all seven basin states.

Agriculture is an important source of employment and income to the local population in the Grand Valley area. In 1972, the annual per capita income for Mesa County was $3,409 compared to the Colorado per capita income of $4,006. The unemployment is generally less than the state-wide level (in October 1976 it was 4.3 percent compared to 5.3 percent for the state). In 1970, the median income for families was $8,065 for Mesa County. Farm population in Mesa County for 1970 was 3,898 which was a 42.7 percent decline from 1960.

The Grand Valley contains approximately 65 percent of the total irrigated croplands in Mesa County and accounts for about 75 percent of total value of farm products for the county. The 1969 census counted a total of 1,320 farms (by U.S. Department of Commerce definition) for Mesa County which was a 21 percent decrease since 1964.

The diversified agricultural industry in the Valley is comprised of both livestock and crop production activities. Slightly less than 10 percent of the irrigated acreage is planted to pome and deciduous orchards, the produce of which is processed locally and may be shipped as far as the Atlantic seaboard. The Grand Valley has long been a favored wintering area for cattle and sheep which are grazed on high mountain summer ranges to the east and north (Young et al., 1975).

An economic survey by Leathers (1975), along with the land use inventory by Walker and Skogerboe (1971), indicates that local farming is primarily a small unit operation. The population engaged in agricultural activities is widely dispersed throughout the Valley with most living on their property. Leathers (1975) determined from 100 random selections that most farm units were less than 40 hectares (100 acres) in size (Figure 10). Using data supplied by the USDA Soil Conservation Service, frequency distribution of field sizes is shown in Figure 11. Of the total of 7870 fields in the Valley, 50 percent are less than 2 hectares in size.

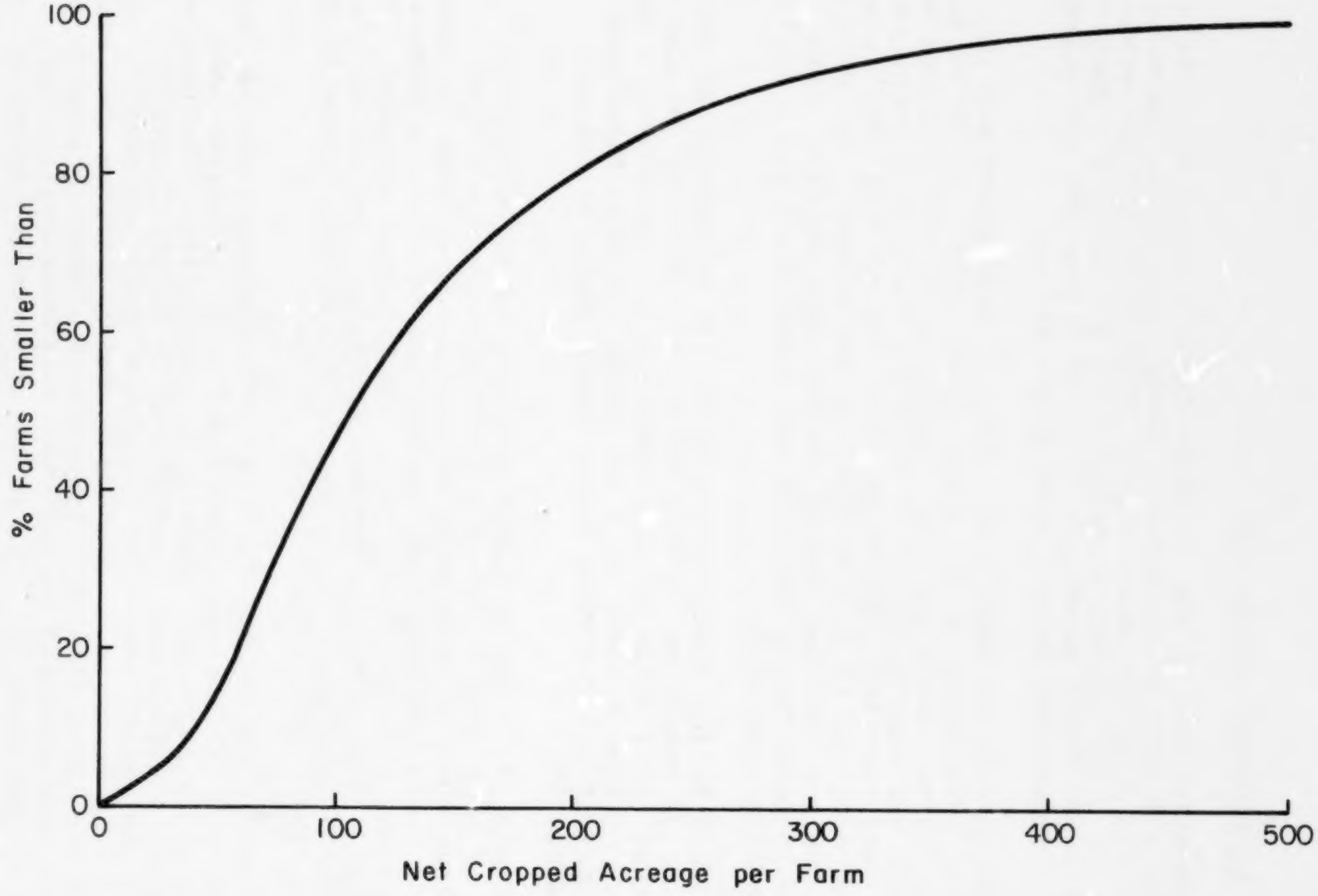

Figure 10. Frequency distribution of farms in the Grand Valley (Leathers, 1975).

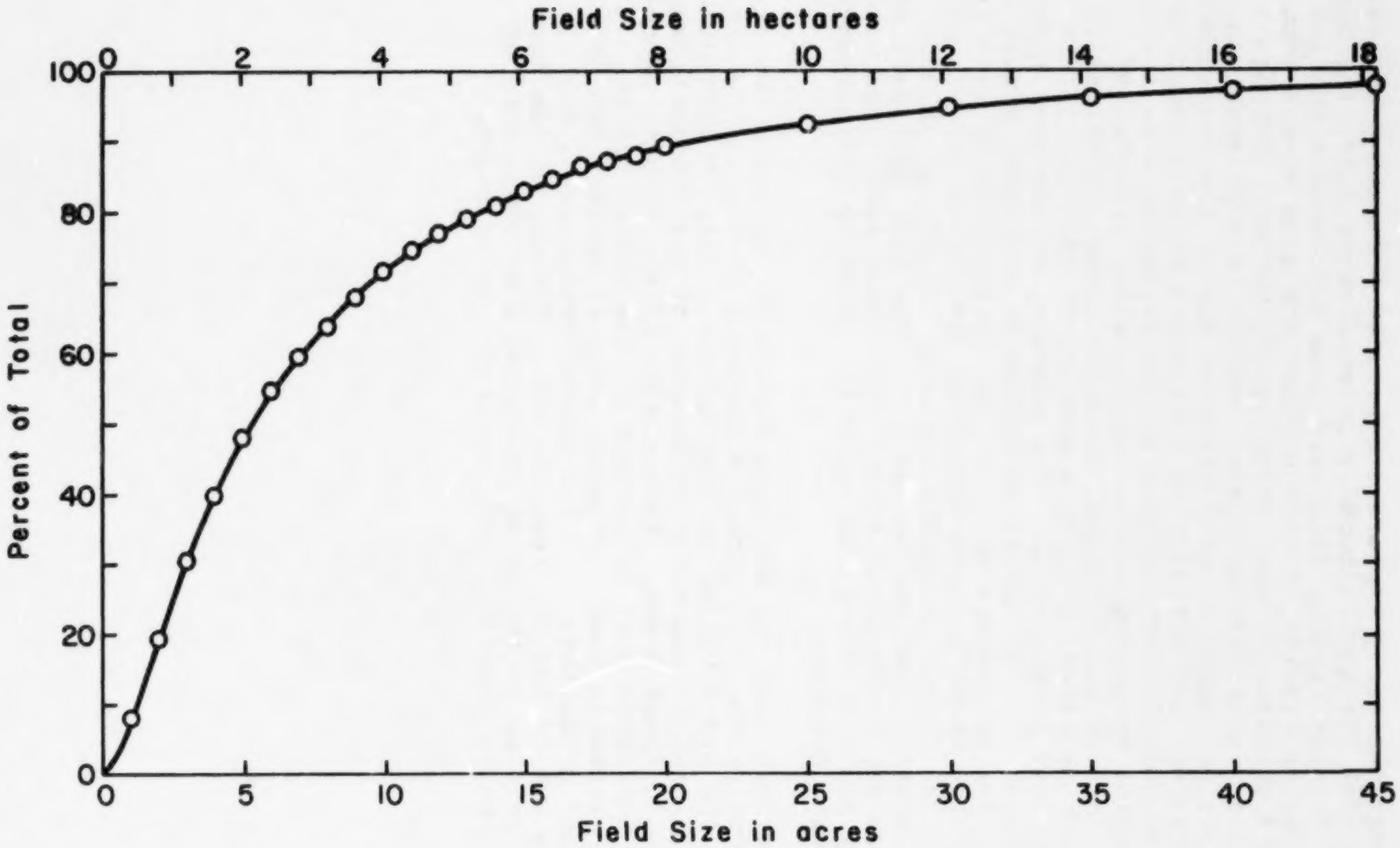

Figure 11. Frequency distribution of field sizes in the Grand Valley (USDA-SCS, 1976).

AGRICULTURAL LAND USE

Although the early explorers concluded that the Grand Valley was a poor risk for agriculturally related activities, the first pioneering farmers rapidly disproved this notion with the aid of irrigation water diverted from the Grand and Blue Rivers (now the Colorado and Gunnison Rivers) entering the Valley. Through a long struggle, an irrigation system evolved to supplement the otherwise meager supply of precipitation during the hot summer months. However, the futility of irrigation without adequate drainage was quickly demonstrated in the Valley as some low lying acreages became waterlogged with highly saline groundwater. Today, the failure to completely overcome these conditions is still evident as illustrated by a summary of land use in the Valley presented in Figure 12. For example, of the more than 28,600 hectares (70,000 acres) or irrigable cropland, almost one-third is either in pasture or idle. An examination of land use in Grand Valley by Walker and Skogerboe (1971) indicated a large fraction of the 12,000 to 16,000 hectares (30,000 to 40,000 acres) of phreatophytes and barren soil were also once part of an irrigated acreage. Evidence exists that these same lands were once highly productive and subsequently ruined by overirrigation and inadequate drainage.

The various land use acreages in the Valley are shown in Table 3. One of the most quoted statements in the literature concerning the Grand Valley is that approximately 30 percent of the farmable area is unproductive because of the ineffectiveness of drainage in these areas. Examination of the results presented in Table 3 indicates that 58 percent of the valley can be classified as usable land. However, only 43 percent can actually be considered productive. In the demonstration area, the percentages are 70 and 52, respectively. The use of the term productive relates to the areas producing cash crops such as corn, sugar beets, small grains, orchards, and alfalfa.

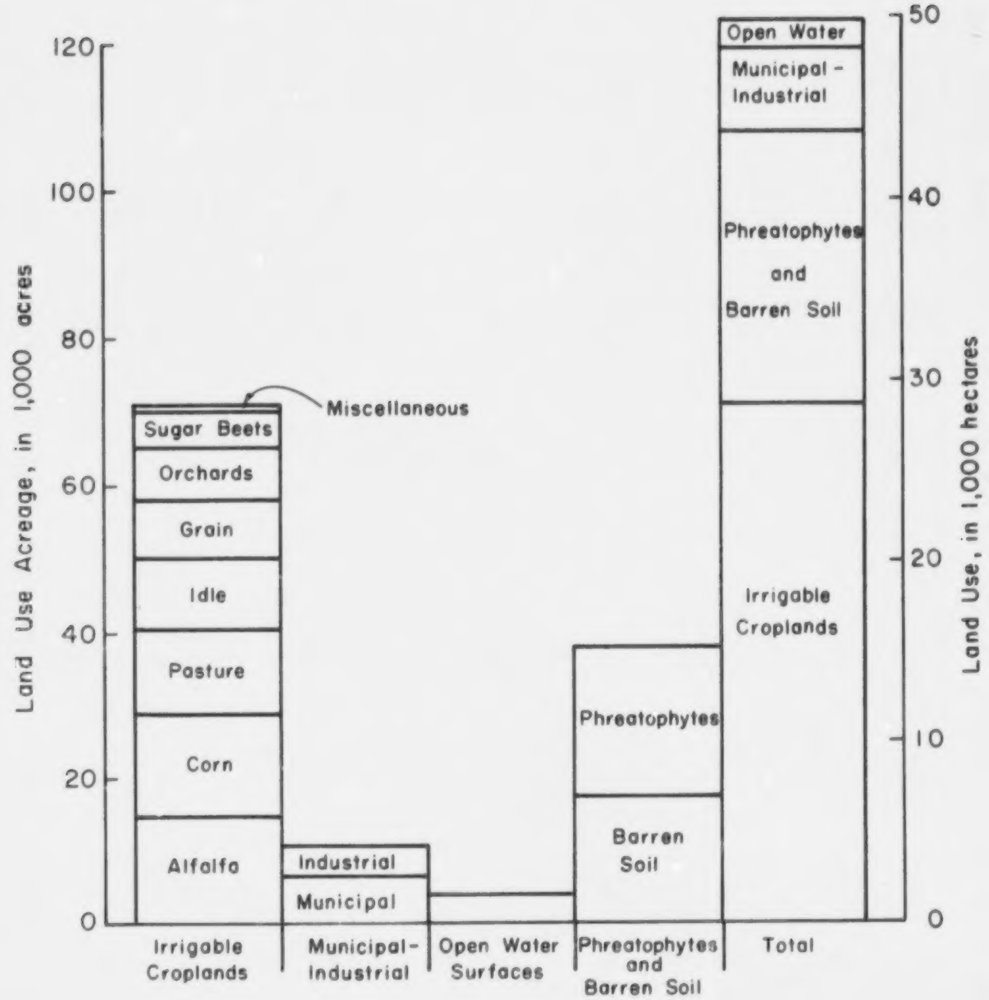

Figure 12. Agricultural land use in the Grand Valley (Walker and Skogerboe, 1971).

TABLE 3. LAND USE SUMMARY BY CANAL IN THE GRAND VALLEY, COLORADO, 1969 (IN HECTARES)

Land Use Classification	Stub Ditch	Gov't Highline Canal	Price Ditch	Grand Valley Canal	Mesa County Ditch	Adjacent to River	Orchard Mesa #1 Canal	Orchard Mesa #2 Canal	Redlands Canal	Redlands Power Canal	Total
Corn	28.7	2419.1	216.5	2699.1	63.5	31.2	284.0	26.3	50.2		5818.6
Sugar beets		1396.7		698.3			20.6		13.0		2128.6
Potatoes		38.4		38.8			31.6		1.2		110.0
Tomatoes		12.5	0.8	53.8			26.7		6.9		100.7
Truck Crop		65.1		59.5			21.4				146.0
Barley	13.6	665.2	106.4	935.0	25.1		82.5	17.4	7.3		1852.5
Oats		389.6	28.3	613.0	6.1		31.2	2.0	22.3		1092.5
Wheat		6.1	8.9	25.5			10.5				51.0
Alfalfa	39.2	2839.9	222.9	2106.3	100.3	64.7	227.6	155.6	164.7	50.2	5971.6
Native Grass Hay			14.2	34.0			4.5	3.6			56.3
Cultivated Grass Hay	2.4	182.1	44.1	619.4	36.4		64.3	21.8	8.5	4.0	983.0
Pasture	17.4	620.3	149.3	1473.6	129.5	2.4	132.7	108.8	458.8	2.0	3094.8
Wetland Pasture		4.5									4.5
Native Pasture		19.0	80.1	217.7	19.8		57.0	1.2	23.4	23.1	441.3
Orchard	99.9	281.2	637.2	208.0	16.6	10.5	668.4	744.9	150.1		2816.8
Idle	44.9	1192.8	231.0	1707.0	136.8	3.6	224.1	143.6	245.6	1.2	3930.6
Other		51.0	2.4	4.5							57.9
Farmsteads	10.1	277.2	43.7	494.0	32.0	2.0	58.3	36.4	27.9	10.1	991.7
Residential yards	2.0	11.3	65.9	13.8	7.7		87.4	11.3	15.4		214.8
Urban	0.8	307.1	106.8	1588.1		17.8	264.6	19.8	273.9	14.6	2593.5
Stock yards		63.5	4.9	97.5	8.5		66.4	7.3	13.0	3.2	264.3
Refineries				16.2							16.2
Miscellaneous Industrial				251.3	8.5	33.6					293.4
Natural Ponds	12.5	256.9	15.0	303.5	19.4	852.5	35.6	19.0	17.8	7.7	1539.9
Cottonwoods (H)[1]	1.6	247.6	4.0	131.5		481.5	15.4	8.9	29.1		919.6
Cottonwoods (M)[1]						53.4	1.6	8.5	1.6		65.1
Cottonwoods (L)[1]				6.1	1.2	68.8	2.8		0.8		79.7
Salt Cedar (H)	0.8	915.2	9.7	525.6	5.7	1073.8	12.3	6.9	338.2	2.0	2890.4
Salt Cedar (M)				6.1	6.1		1.6	5.3			19.1
Salt Cedar (L)				23.9		43.7	20.6				88.2
Willows (H)	2.8	43.7	5.3	54.2		35.6	4.0		24.3		169.9
Willows (M)		1.6	6.5	1.6							9.7
Willows (L)		4.0	4.5								8.5
Cattails (H)		139.2	2.8	170.7	4.5	1.2	17.4		3.6		339.4
Cattails (M)			3.6				8.1	8.9			20.6
Greasewood (H)	6.5	1184.7	5.3	1408.4	68.4	307.5	41.7	87.6	77.7	2.0	3190.0
Greasewood (M)	8.1	82.9		21.4	40.1	27.1	3.6	15.0			198.2
Greasewood (L)	0.8	31.6	25.1	75.7	13.8	3.6	53.4		6.5		210.5
Shrubs: Wild Rose, etc. (H)		1.2						3.6			4.8
Shrubs (M)							2.0	3.6			5.6
Shrubs (L)							3.6				3.6
Grasses and/or sedges (H)							6.9			0.4	7.3
Grasses and/or sedges (L)			4.9	0.4							5.3
Precipitation only	20.6	4219.6	136.4	1432.3	20.6	292.1	186.9	203.1	497.7	2.0	7011.3
TOTAL	312.7	17970.8	2186.5	18115.8	770.6	3406.6	2781.7	1670.8	2479.5	122.5	49817.5

[1] Note: H = Heavy cover, M = Medium cover, L = Light cover

SECTION 5

PRESENT IRRIGATION PRACTICES

WATER SUPPLY

The primary source of water for irrigation in the Grand Valley is the Colorado River, with the exception of about 1200 hectares (3000 acres) which are irrigated from the Gunnison River. There is no groundwater used for irrigation due to the high salinity (8700 mg/l) of the waters in any of the potentially productive aquifers. A schematic representation of the hydrologic budget for the area is presented in Figure 13.

Irrigation water entering into the Grand Valley is of relatively high quality. The electroconductivity ranges from around 350 μmhos/cm to a maximum of 4000 μmhos/cm with the average value being 480 μmhos/cm. Suspended solids concentrations in the incoming irrigation water range from a low of 5 ppm to over 4000 ppm with an average mean of 200 ppm. However, the drains which carry field tailwater often obtain suspended solids concentrations in excess of 30,000 ppm. The USDA Soil Conservation Service estimates that 2.6 million metric tons (2.9 million tons) of sediment are added annually to the Colorado River from the irrigation of lands in the Grand Valley. Municipal water (potable) supplies in the Valley are obtained from a well-developed system of reservoirs on the Grand Mesa and are of a very high quality. This water, however, is much more expensive than irrigation water and, consequently, many homeowners use irrigation water for the irrigation of landscapes and gardens.

Irrigation water costs in the Grand Valley range from $9.90/ha-m ($1.22/AF) to $43.80/ha-m ($5.40/AF) depending on the canal and number of shares. The average cost tends toward the lower value.

WATER RIGHTS

Early exploration concluded that the Grand Valley had limited potential for agriculture since the terrain appeared very desolate. A great deal of appreciation for this judgment can be acquired just passing through the area and noting the landscape outside the irrigated agricultural boundaries. In 1853, Beckwith (the expedition recorder for the Captain John W. Gunnison

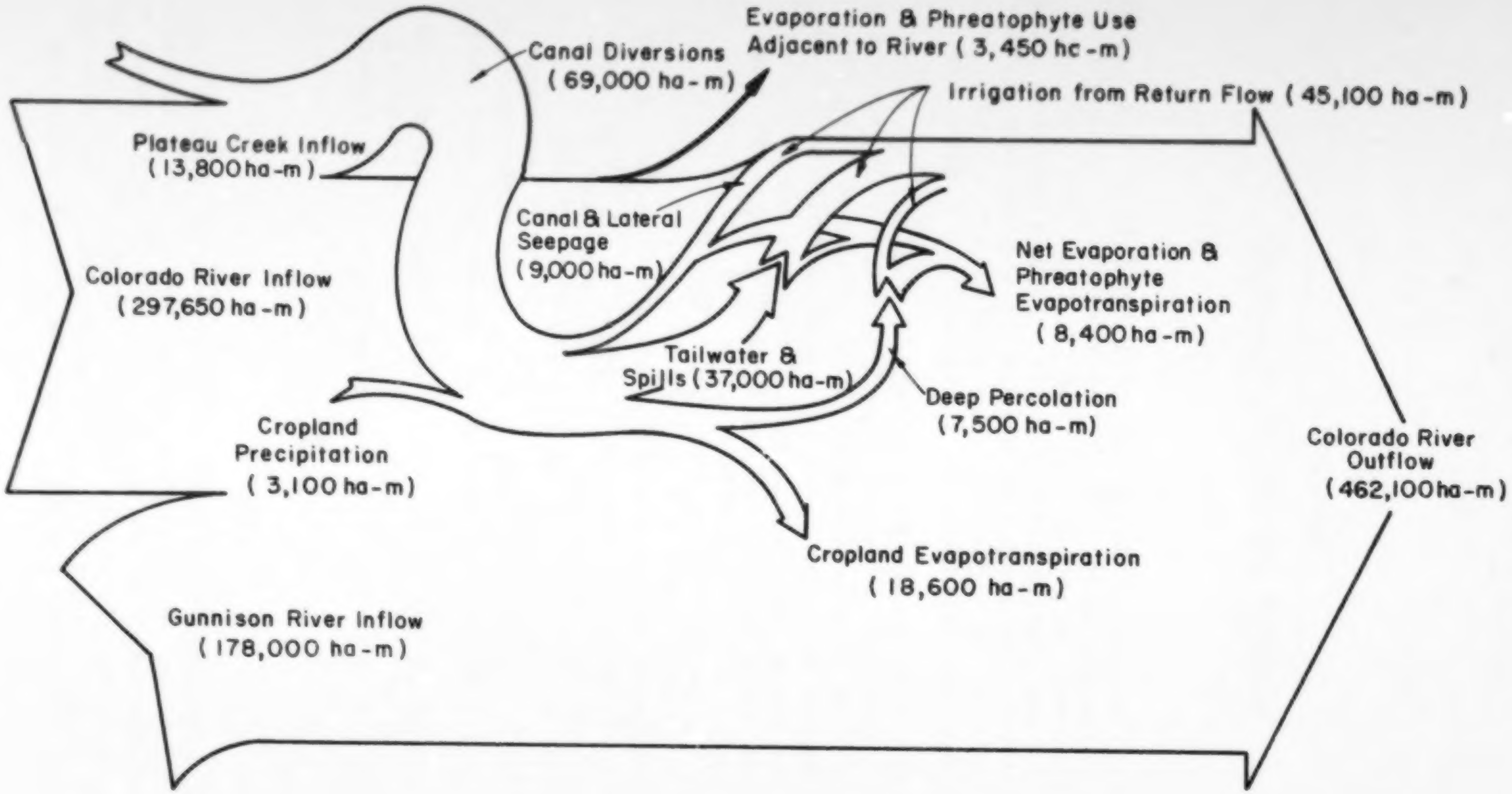
Evaporation & Phreatophyte Use
Adjacent to River (3,450 hc-m)
Canal Diversions
(69,000 ha-m)
Irrigation from Return Flow (45,100 ha-m)
Plateau Creek Inflow
(13,800 ha-m)
Canal & Lateral
Seepage
(9,000 ha-m)
Net Evaporation &
Phreatophyte
Evapotranspiration
(8,400 ha-m)
Colorado River Inflow
(297,650 ha-m)
Tailwater &
Spills (37,000 ha-m)
Deep Percolation
(7,500 ha-m)
Cropland
Precipitation
(3,100 ha-m)
Colorado River
Outflow
(462,100 ha-m)
Cropland Evapotranspiration
(18,600 ha-m)
Gunnison River Inflow
(178,000 ha-m)

Figure 13. Graphic representation of the magnitude and distribution of water flows in the Grand Valley for 1968 (Walker, 1970).

exploration, 1853) described the Valley as, "The Valley, twenty miles in diameter, enclosed by these mountains, is quite level and very barren except scattered fields of greasewood and sage varieties of artemisia--the margins of the Grand (Gunnison) and Blue (Colorado) River affording but a meager supply of grass, cottonwood, and willow." Soon after the settlement began (September, 1881), it was realized that the climate could not support a nonirrigated agriculture. As a result, irrigation companies were organized to divert water from the river for irrigation. A map of the irrigation canal system in the Grand Valley is presented in Figure 14.

The first such company was the Grand Valley Irrigation Company who owns and operates the Grand Valley Canal, and, at the present time, serves 18,890 hectares (46,678 acres) of land, although in the 1969 land use survey, only 12,030 hectares (29,727 acres) were irrigated.

The present Grand Valley Canal system comprising approximately 124.4 kilometers (77.25 miles) of canals and subcanals is the result of a consolidation of the Grand River Ditch Company, Grand Valley Canal Company, Mesa County Ditch Company, Pioneer Extension Ditch Company, and the Independent Ranchmen's Ditch Association. The construction of what is now the main line Grand Valley Canal probably began in 1882 since the original priority is dated August 22, 1882, although A. J. McCune who was the engineer for the Grand River Ditch Company filed a statement with the clerk and recorder of Mesa County, Colorado on April 5, 1883, that construction commenced January 10, 1883. At this time, the ditch was owned by Matt Arch, E. S. Oldham, William Oldham, John Biggles, and William Cline who planned for a capacity of about 786 cfs (22.26 cms). The times of the early development were uncertain and the company, like so many others, was facing financial trouble. It was then sold to the Traveler's Insurance Company which also acquired title to the other four companies now making up the system. On January 29, 1894, the Grand Valley Irrigation Company was incorporated when the Certificate of Incorporation was filed with the Secretary of State's office and the title was acquired from the insurance company.

Although the original decree was based on an estimated acreage of 30-35,000 acres (12,500-14,600 hectares), later investigations revealed the acreage was slightly less than 40,000 acres (16,700 hectares), plus an additional 4,661.25 acres (1,942.19 hectares) not yet developed, for a total of about 44,000 acres (18,300 hectares). If the usual 200-day irrigation season is experienced, this water right amounts to approximately 1.76 hectare-meters/hectare (5.76 acre-feet per acre) on a total irrigated area basis, from which an estimated 20 percent seepage loss rate of 0.32 hectare-meters per hectare (1.05 acre-feet per acre) leaves about 1.44 hectare-meters per hectare (4.71

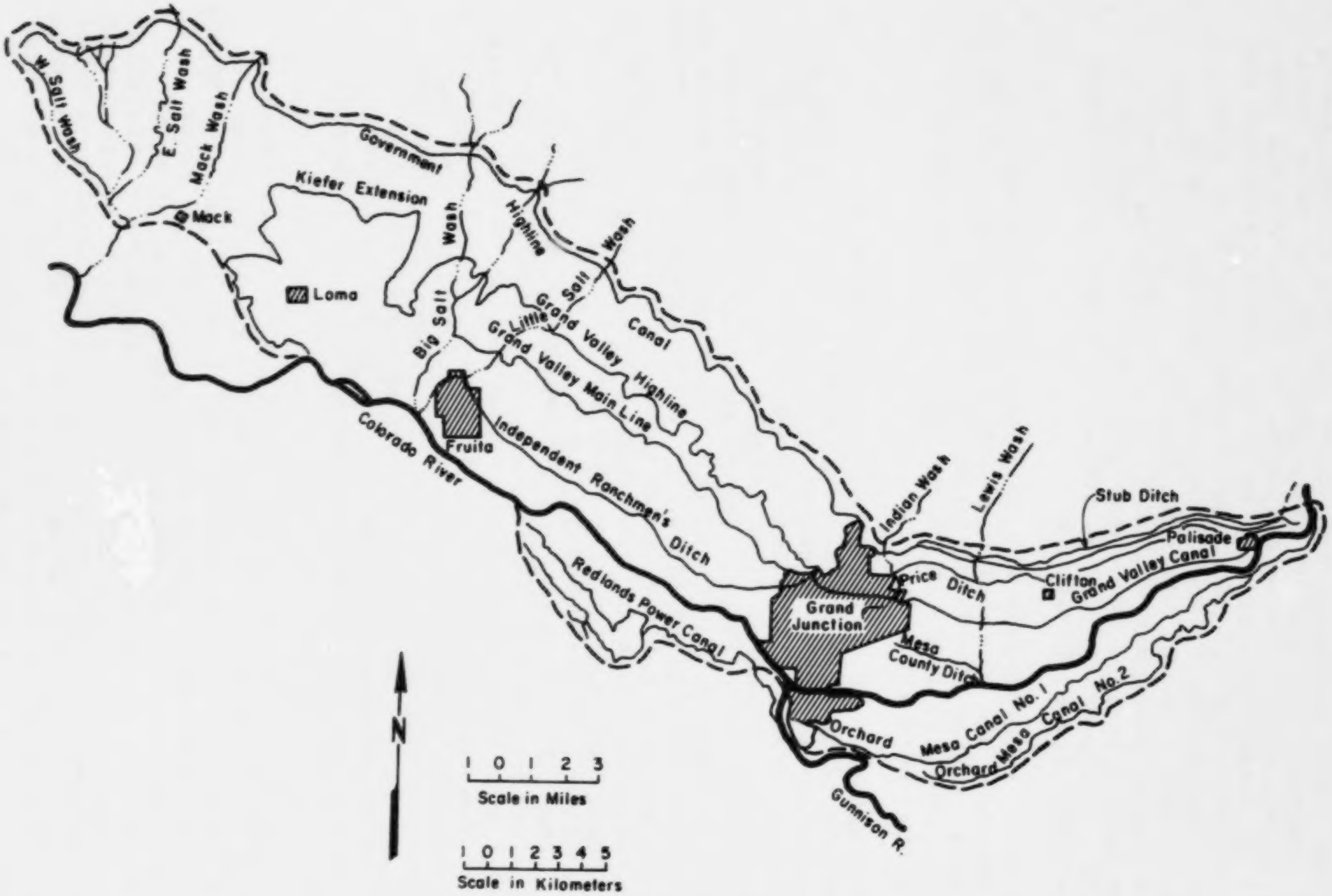
W. Salt Wash
E. Salt Wash
Mack Wash
Mack
Government
Kiefer Extension
Loma
Wash
Highline
Salt Wash
Big Salt
Little
Grand Valley Highline
Canal
Grand Valley Main Line
Fruita
Colorado River
Independent Ranchmen's Ditch
Redlands Power Canal
Indian Wash
Lewis Wash
Stub Ditch
Palisade
Clifton
Grand Valley Canal
Price Ditch
Grand Junction
Mesa County Ditch
Orchard Mesa Canal No. 1
Orchard Mesa Canal No. 2
Gunnison R.
N
1 0 1 2 3
Scale in Miles
1 0 1 2 3 4 5
Scale in Kilometers

Figure 14. Grand Valley canal distribution system.

acre-feet per acre) for irrigation. The water right based on the net irrigated area is much higher, approaching 2.60 hectare-meters per hectare (8.53 acre-feet per acre) and 2.08 hectare-meters per hectare (6.82 acre-feet per acre), respectively.

The Grand Valley Project (built by the USDI, Bureau of Reclamation) serves water to four irrigation companies, the Grand Valley Water Users Association, the Orchard Mesa Irrigation District, Palisade Irrigation District (Price Ditch), and the Mesa County Irrigation District (Stub Ditch).

The Grand Valley Water Users Association was incorporated February 7, 1905, and later renewed the incorporation September 11, 1945. It operates the Government Highline Canal which serves about 18,507 hectares (44,416 acres) of irrigable land. In 1969, 10,186 hectares (25,169 acres) were irrigated under this canal. In addition, the Association diverts 22.60 cms (800 cfs) during the nonirrigation season for power development through a siphon across the Colorado River shortly below the main diversion. During the irrigation season, 11.30 cms (400 cfs) is used for power development, with the remaining 11.30 cms (400 cfs) passing through the irrigation pumps to raise the irrigation water to the Orchard Mesa Canals. The power generated with this water is sold to the Public Service Company of Colorado to help pay the debt on the original project. The length of the Government Highline Canal is 73.7 km (45.8 miles).

The Orchard Mesa Division of the Grand Valley Project was formed by request of the people of the Orchard Mesa Irrigation District when the prior operation was facing bankruptcy. The District was organized under the 1905 Colorado Statute covering irrigation districts, which was later revised to comply with the 1921 Colorado law.

The operation of the Orchard Mesa Irrigation District in many ways is similar to the Association in that the water duty and land classification are the same. The District is now provided water through the siphon diversion under the Colorado River from the Government Highline Canal into the Orchard Mesa Power Canal (3.9 km in length). During the irrigation season, 1/2 of the 22.60 cms (800 cfs) in the canal is diverted through the Orchard Mesa Irrigation District pumps which lift 2.27 cms (80 cfs) 12.2 meters (40 feet) into the Orchard Mesa #2 Canal (26.1 km in length) and 1.70 cms (60 cfs) 39.3 meters (130 feet) into the Orchard Mesa #1 Canal (24.1 km in length). The Orchard Mesa system serves 3114 irrigated hectares (7694 acres) according to the 1969 land use survey.

The Palisade Irrigation District, with essentially the same organizational format as the Orchard Mesa Irrigation District, operates the Price Ditch (9.5 km). This ditch is supplied 1.87-1.93 cms (66-68 cfs) through a turbine pump just off the

Government Highline Canal as it exits through Tunnel No. 3. An additional 0.68 cms (24 cfs) is delivered under a carriage contract through turnouts in the Highline Canal. There were 1743 hectares (4306 acres) irrigated directly under this canal in 1969.

The Mesa County Irrigation District, which operates the Stub Ditch (11.3 km) has an irrigation water right of 1.13 cms (40 cfs). The operation and organization of this district are similar to the previous five districts mentioned. At the turbine pump serving the Price Ditch, 0.42 cms (15 cfs) are pumped into the Stub Ditch. The remaining 0.71 cms (25 cfs) is diverted under a carriage contract directly from the Highline Canal to agricultural lands within the boundaries of the Mesa County Irrigation District. A total of 246 hectares (608 acres) was irrigated directly from this canal in 1969.

Both the Palisade Irrigation District and the Mesa County Irrigation District were organized independently of the government projects. Their history is somewhat unknown to the writers, but they consolidated their systems with the Highline Canal when it was built, presumably to streamline their operation and to eliminate operation and maintenance costs of the individual diversion works which can be substantial. The old river diversion works (now abandoned) can still be seen just above the town of Palisade.

The Redlands Water and Power Company, a mutual ditch company, irrigates about 1200 hectares (3000 acres) southwest of Grand Junction and south of the Colorado River in a canal carrying 8.97 cms (670 cfs). Under this diversion 0.17 cms (6 cfs) is used for irrigation of lands below the power canal, 17.24 cms (610 cfs) for power generation, and 1.53 cms (54 cfs) is pumped to an initial height of 38.7 meters (127 feet) for irrigation. Small areas in the project are served by higher lifts. The highest is about 91.4 meters (300 feet). Electricity in excess of pumping needs is sold to project settlers and to the Public Service Company. Much of the lands served by these canals is residential.

The water rights of the individual canals and the priorities are listed in Table 4. The dimensions, capabilities, and seepage rates of the canals in the Grand Valley are tabulated in Table 5.

CANAL OPERATIONS

The canals are operated by the previously mentioned canal companies. These companies are relatively small with small staffs compared to similar organizations in other irrigated areas in the western United States. Generally speaking, maintenance of canals and headgate regulation are kept to a minimum. The Government Highline, however, does have a limited demand type

TABLE 4. WATER RIGHT DECREES FOR THE GRAND VALLEY IRRIGATED AREA

Name of Ditch	Original Appropriation Date	Decree Allowed (cfs)[1]	Use of Right	Comments[2]
(1) Orchard Mesa Power Canal	3-6-89	110.70	Irrigation	Abandon, land now in Orchard Mesa Irr. Dist., 10 cfs irr., rest pumping, rights not transferred to District
(2) Palisade Irr. Dist.	10-1-89	573.00	Pumping	Power plant abandon, decree usable only with approval of Bureau of Reclamation.
(3) Palisade Irr. Dist.	10-1-89	80.00	Irrigation	Decree delivered by Gov't Highline Canal, point of diversion changed by decree of 7-25-41 (Price Ditch).
(4) Orchard Mesa Power Canal	8-2-98	139.30	Irrigation	Same as (1).
(5) E. Palisade Irr. Dist.	10-1-00	10.20	Irrigation	Former steam pumping plant, now gravity from Orchard Mesa Power Canal, Orchard Mesa Irr. Dist. owns decree.
(6) Mesa County Irr. Dist.	7-6-03	627.00	Pumping	Same as (2), (Stub Ditch).
(7) Mesa County Irr. Dist.	7-6-03	40.00	Irrigation	Decree now delivered by Gov't Highline Canal by gravity and pumping, point of diversion not formally changed.
(8) Mann Pumping System	9-10-03	1.00	Irrigation	Former steam pump from river, now pumped from Orchard Mesa Power Canal, electric motor.
(9) Orchard Mesa Irr. Dist.	10-25-07	195.00	Irr. Pump	Now diverted through Gov't Highline Canal, but through same pumping plant, point of diversion changed.
(10) Orchard Mesa Irr. Dist.	10-25-07	75.00	Irrigation	Same as (9).
(11) Orchard Mesa Irr. Dist.	10-25-07	180.00	Conditional	Same as (9), made absolute in decree of 7-25-41, 130.0 cfs power, 50 cfs irrig.
(12) Grand Valley Project	2-27-08	730.00	Irrigation	Quantity fixes in decree of 7-25-41 as above, same applies for power and domestic.
(13) Grand Valley Project	2-27-08	400/800	Power	Quantity fixed in decree of 7-25-41 with priority date as above, 400 cfs irrigation season, 800 cfs non-irrigating season.
(14) Rose Point Power Canal	7-2-10	113.25	Irrigation	Abandon, decree property of Orchard Mesa Irr. Dist., no change in point of diversion.
(15) Orchard Mesa Irr. Dist.	4-26-14	100.00	Conditional	Conditional water claimed for irrigation, none claimed for pumping water.
(16) Palisade Irr. Dist.	6-1-18	23.50	Irrigation	Date of this decree is date of change of point of diversion to Gov't Highline Canal (3). This decree provides for laterals fed directly from project canal to Palisade lands.
(17) Grand Valley Irrigation Company	7-27-12	520.81	Irrigation	Priority Date of 8-22-82, No. 1 priority on the Colorado River. Based on 30-35 thousand acres w/20 percent loss rate.
(18) Grand Valley Irrigation Company	7-25-14	195.33	Irrigation	First enlargement, Priority 358 of which 75.86 cfs is conditional upon the addition of 4661.25 acres to the system.
(19) Redlands Water & Power Company		670.00	Irrigation & Power	60 cfs used for irrigation. Water is diverted from the Gunnison River.

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[1] 1 cfs = 0.0283 m^3/sec

[2] Decrees (1) through (16) are water right decrees incorporated in the Grand Valley Project.

TABLE 5. DIMENSIONS, CAPACITIES AND SEEPAGE RATES OF CANALS IN THE GRAND VALLEY, COLORADO

Canal	Length Km	Inlet Q m^3/sec	Wetted Perimeter m	Days of Operation per Year	Effective Seepage Rate $m^2/m^3/day$	Seepage m^3/day	Salt Contribution m. tons/yr
Government Highline	73.7	16.99	19.19	214	0.076	77,300	54,100
Grand Valley	19.8	18.41	16.67	214	0.030	10,900	7,600
Grand Valley Mainline	21.7	7.08	13.86	214	0.046	10,800	7,600
Grand Valley Highline	37.0	8.50	12.62	214	0.046	22,100	15,400
Kiefer Extension	24.5	3.96	7.25	214	0.046	6,800	4,800
Mesa County	4.0	1.13	6.67	214	0.046	600	700
Independent Ranchman's	17.4	1.98	3.17	214	0.046	2,600	1,800
Price	9.5	2.83	7.27	214	0.046	2,200	1,600
Stub	11.3	0.85	2.94	214	0.046	1,400	1,000
Orchard Mesa Power	3.9	24.07	8.20	365	0.061	3,300	2,300
Orchard Mesa No. 1	24.1	3.02	6.46	214	0.061	7,400	5,100
Orchard Mesa No. 2	26.1	1.98	3.58	214	0.061	4,800	3,300
Redlands Power	2.9	24.07	16.88	365	0.050	1,900	1,300
Redlands No. 1 and No. 2	10.8	1.70	3.95	214	0.122	4,200	2,900
TOTAL CANALS	286.7					156,300	109,500

lateral diversion system, but the water deliveries are measured only infrequently.

Adjusting the amount of the canal diversions at the river is also kept to a minimum. Regulation of water within the canal system is controlled by spillage into drains and natural washes. This water contributes very little to the salt loading from the Valley, but is often 20 percent to 25 percent of the total diversion. This is obviously a luxury which can be taken only in an area with abundant water and very senior water right appropriations.

If the canals would go to a strict demand type delivery system, the spillage would be negligible but would entail the general acceptance of more efficient irrigation methods such as trickle, sprinklers, borders, dead-level irrigation, cut-back irrigation, tailwater recovery systems, automation and changes in present tillage practices. It would require that the canal companies hire additional staff and purchase more equipment. The present very low cost of water would have to increase substantially to pay for these services.

LATERAL OPERATION

There are several hundred laterals (1553 not including the Redlands) in the Grand Valley covering a distance of more than 600 kilometers. The term lateral is read in this text to refer to those small conveyance channels that deliver waters from the company canals to the farmer's fields, and are defined as the distance from the headgate to the point of delivery to the last farm. These small channels usually carry flows less than 0.14 cms (5 cfs) and range in size up to 1.2 or 1.5 meters (4 or 5 feet) of wetted perimeter.

When water is turned into the lateral system, it becomes the responsibility of the users entitled to the diversion and not the ditch company. The only exception is that the Grand Valley Water Users Association (Government Highline Canal) which will treat some of their larger laterals as small canals and loosely manage the water within the lateral by regulation of the "sublaterals." However, no effort is made to control the water use in the sublaterals or on the farm.

Single users served by an individual canal turnout are not uncommon, but most laterals serve several irrigators who decide among themselves how the lateral will be operated. Most of the multiple-user laterals, which may serve as many as 100 growers, run continuously throughout the irrigation season with unused water being diverted into a convenient drainage channel.

Data collected during the course of the investigations indicate that as the size of the laterals approaches 48-50 hectares (120-125 acres) and/or have more than 2-4 users, they will run continuously throughout the season. A frequency distribution of the laterals in the Valley is presented in Figure 15. The longest lateral in the Valley is 8990 meters (29,500 feet) as defined by the USDI, Bureau of Reclamation, 1975 (the length of a lateral is from the headgate to the last farm delivery). The largest lateral in the Valley is under the Government Highline Canal and contains 707.81 hectares (1749 acres). The areal distribution of laterals for the Valley is graphically presented in Figure 16.

Under the Stub Ditch, Price Ditch, and Government Highline Canal (east of Indian Wash), the water is allocated on a per acre basis and can never be transferred from the land. The allocation is 0.5 Colorado Miners Inches (CMI) per acre (0.91 l/s/ha) and must run continuously under the by-laws of the Palisade Irrigation District (Price Ditch) and the Mesa County Irrigation District (Stub Ditch). It should be noted that west of Indian Wash, where the Government Highline Canal is not serving lands under carriage contracts, the water is provided on a modified demand basis varying from 0.75 to 1.0 cfs per 40 acres (0.021 to 0.028 m^3/s per 16.2 hectares).

The Grand Valley Canal which diverts water from the Colorado River releases water to the Mesa County Canal and several others are entirely privately owned and have an arrangement by which the water shares are bought, sold, rented, or transferred anywhere in the entire system. One share of water is 0.4 Colorado Miners Inches (0.30 l/s).

ON-FARM WATER USE

The common irrigation philosophy concerning water duty is one share (4.7 to 5.8 gpm or 0.30 to 0.37 l/s) for one acre, continuous flow, which was a reasonable criterion when the canal systems were first established. For example, if a farmer had 80 (32.4 hectares) acres, had 80 shares of water, and, if the total allotment of water was rotated around the farm, the irrigations were fairly efficient. However, since that time, average farm units have become much smaller, and using the same criterion of 1 share per acre, the irrigations obviously had to become less efficient because corresponding smaller streams of water have slower advance times and, therefore, a greater opportunity time for larger amounts of deep percolation.

Practically all irrigations in the Valley utilize open ditches with siphon tubes on row crops with 30-inch row spacings. On crops such as alfalfa and small grains, the irrigations are usually a variation of flood irrigation using "corrugations" or

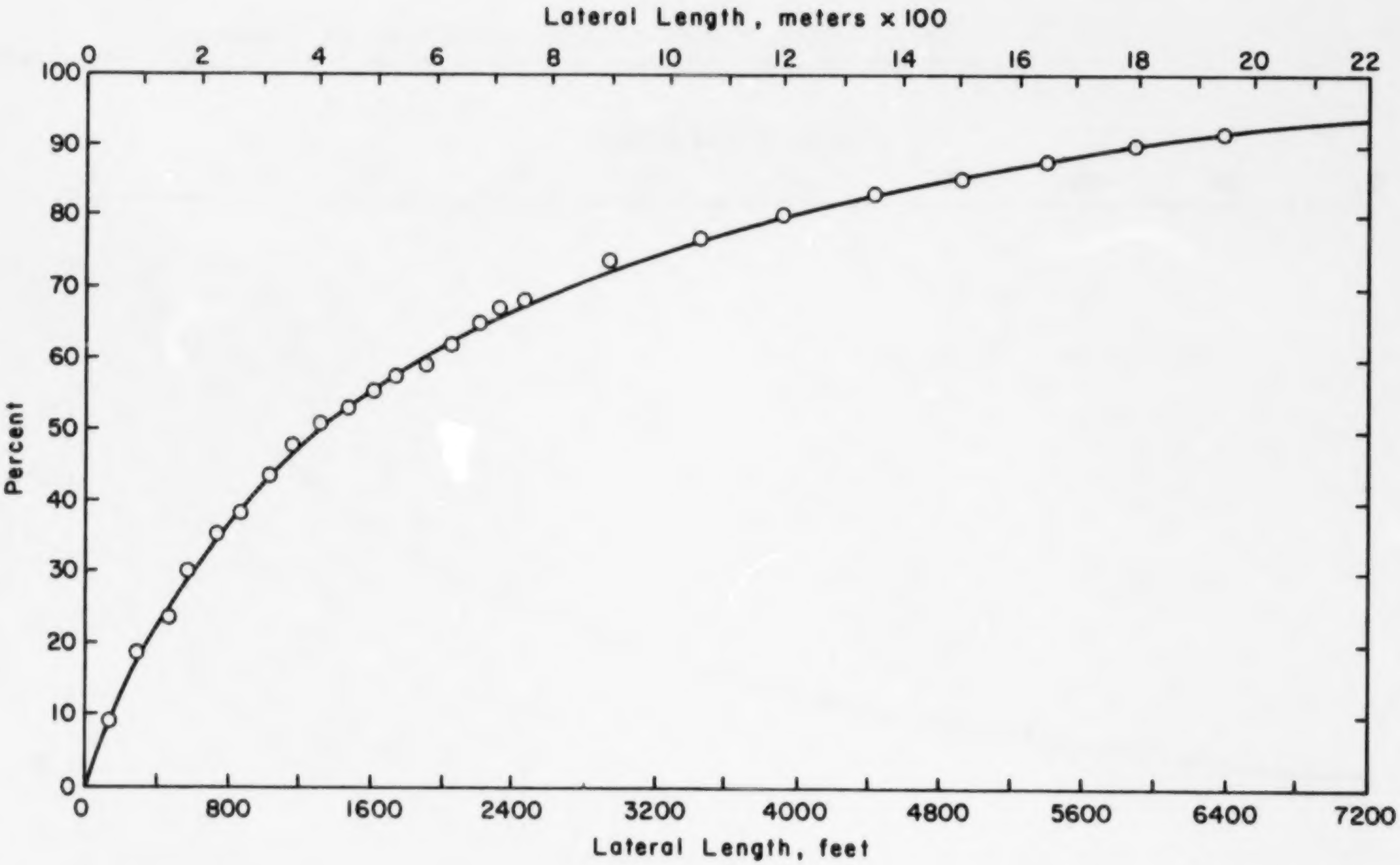


Figure 15. Frequency distribution of lateral lengths in the Grand Valley (USDI, USBR, 1975).

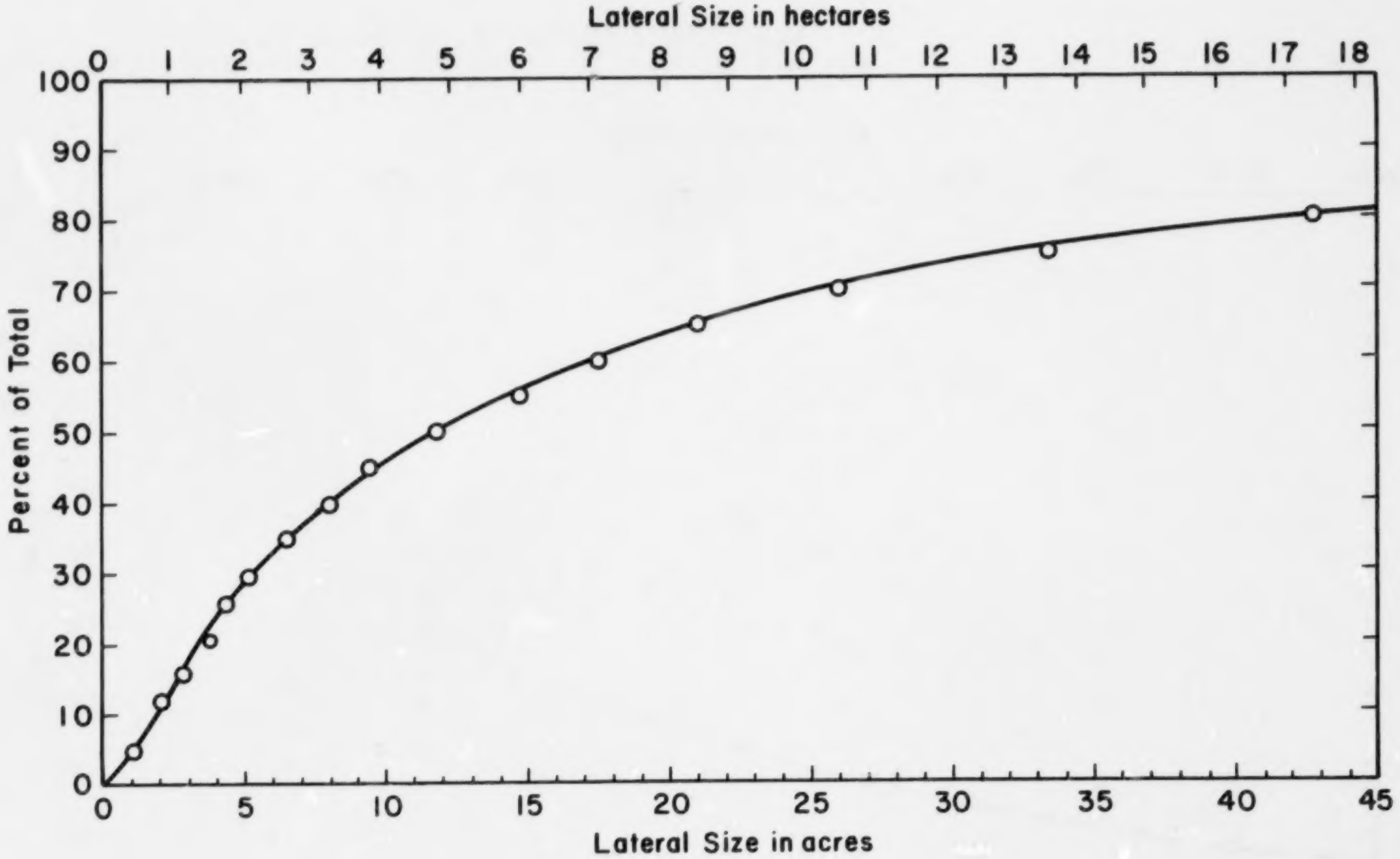


Figure 16. Frequency distribution of the area contained under laterals in the Grand Valley (USDI, USBR, 1975).

shallow furrows, and siphon tubes or a "cut-and-dam" system with some unlined ditches. According to the USDA-SCS (1976), there are more than 1640 km of head ditches in the Valley of which about 1300 km are unlined.

There is very little automation of irrigation systems in the Valley. The only automated systems, other than on turf applications, were installed for demonstration or research purposes by governmental agencies.

The USDA Soil Conservation Service inventory of irrigation practices in the Grand Valley indicates that there are 7870 fields with the average size about 2.2 hectares (5.5 acres) (see Figure 11). The average field width (Figure 17) is about 140 meters (450 feet); the average field length (Figure 18) is approximately 159 meters (520 feet); and the average field slope (Figure 19) is close to 1.25 percent.

The majority of irrigated soils in the Grand Valley are clay loams, with 29.5 percent of the total irrigated acreage being classified as Billings silty clay loam. The soils are generally tight with intake characteristics decreasing with time through the irrigation season (Figure 20).

Because of the low cost of water, the common philosophy of the Grand Valley agricultural community regarding irrigation improvement is limited to concrete linings and land shaping rather than installation of more efficient and sophisticated irrigation methods, which are generally not economically warranted. This attitude is partly the result of national USDA Agricultural Stabilization and Conservation Service (ASCS) regulations on cost sharing which do not allow matching funds for moveable sprinklers and gated pipe (or other types of "portable" systems).

The USDA Soil Conservation Service estimates that approximately one-fifth of the head ditches and laterals in the Grand Valley have been lined, although some are undoubtedly in need of repair. Many of the irrigation leaders in the area proudly point to this fact as a sign of local progressive irrigation practices.

A very common and generally necessary irrigation practice is to plant the crops and irrigate them "up." Furrows are usually on a 30-inch (76 cm) spacing, and the seeds are planted halfway between two furrows. Under this practice, individual irrigation sets often run 36 to 48 hours until the field has become "blacked" out (the water has completely soaked across all the area between furrows). This first irrigation is unquestionably the water application which has the largest contribution to deep percolation and could probably be reduced by changing tillage practices, i.e., planting on the edge of a furrow rather than in

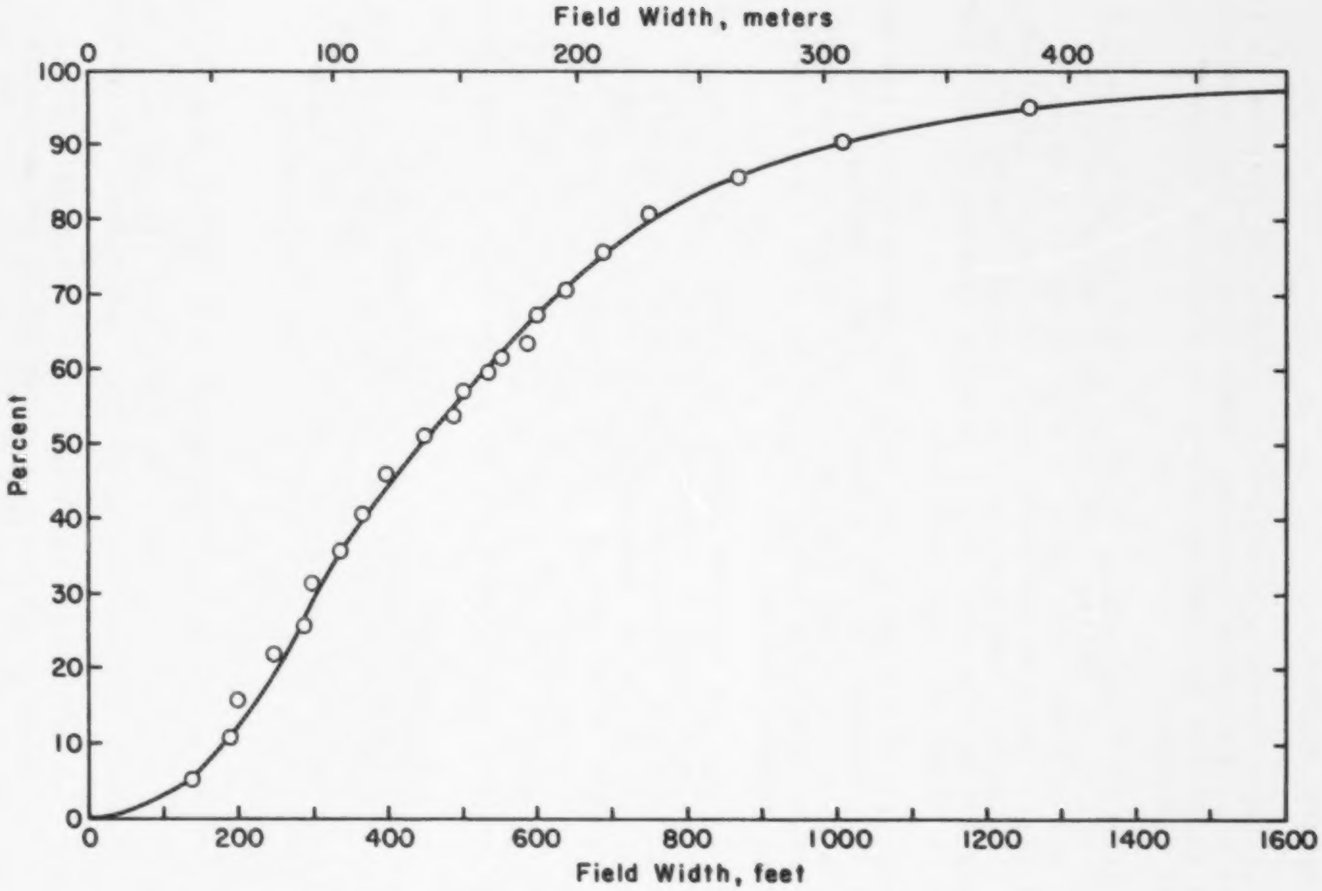


Figure 17. Frequency distribution of field widths in the Grand Valley (USDA-SCS, 1976).

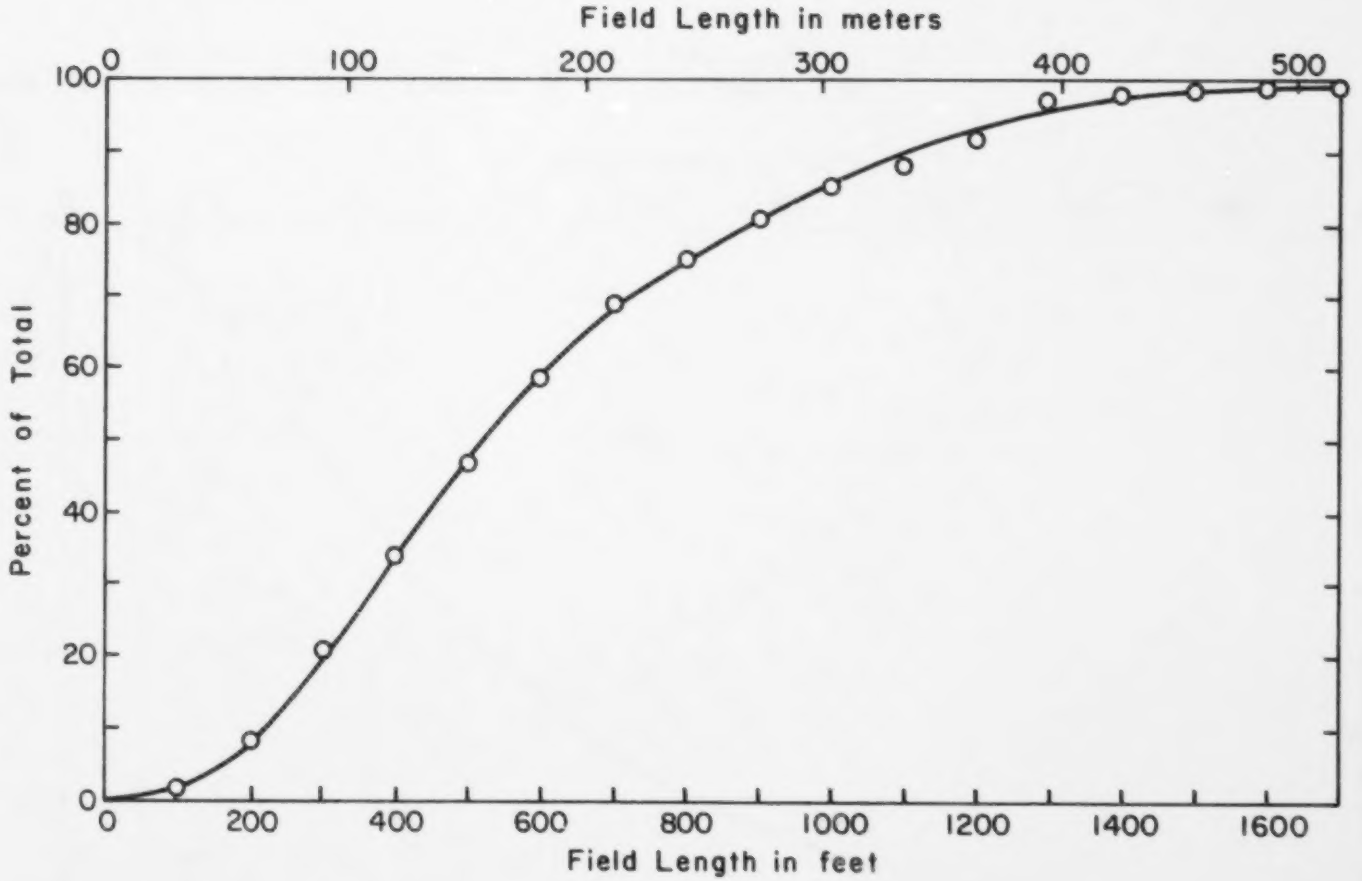


Figure 18. Frequency distribution of field lengths in the Grand Valley (USDA-SCS, 1976).

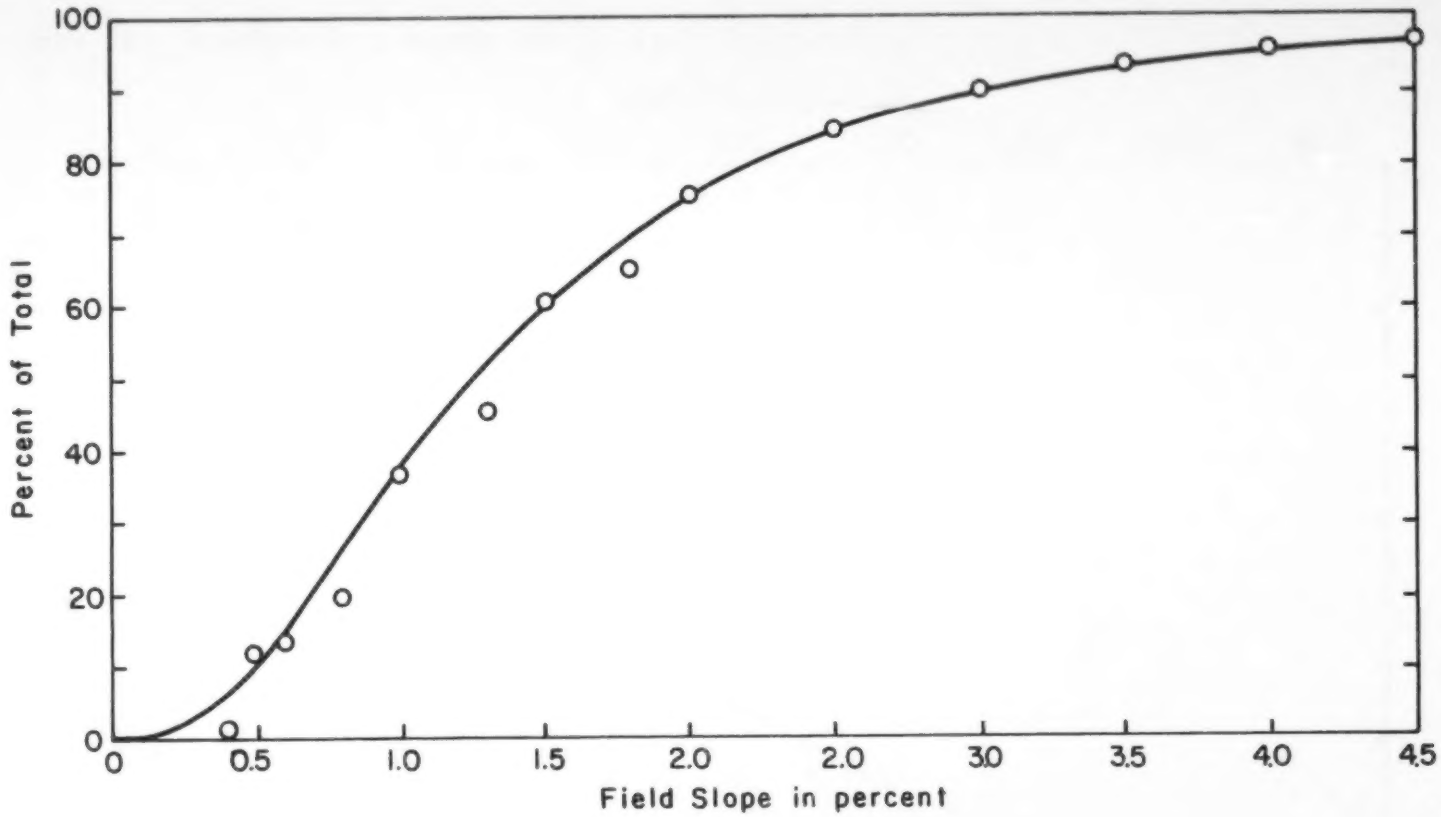


Figure 19. Frequency distribution of field slopes (in percent) in the Grand Valley (USDA-SCS, 1976).

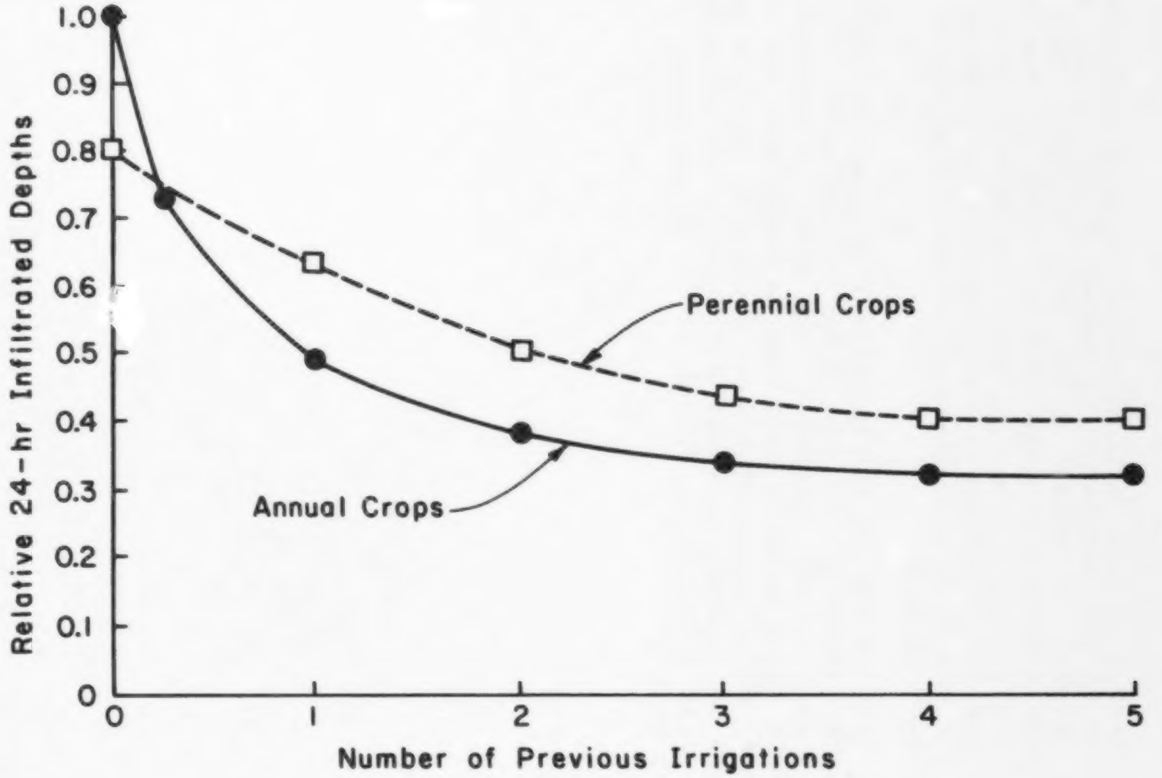


Figure 20. Relative infiltration rate function for perennial and annual crops in the Grand Valley.

the center. However, attempts to introduce new tillage practices into the area have met with limited success. The percent of annual salt pickup during the irrigation season is graphically indicated in Figure 21.

TAILWATER REMOVAL

Field tailwater is the responsibility of each individual irrigator. Most of the tailwater is dumped directly into drains or into other laterals or canals where it is reused. Very few tailwater ditches run much farther than the width of the field before they are put into a drain or other conveyance system. There is only one tailwater recovery (pump-back) system in the Valley which was put in by the Colorado Water Conservation Board as a demonstration project.

The many open drains in the Grand Valley play an important role in tailwater removal. In the demonstration area, these drains carry only about 27 percent of the total groundwater flows, and their major benefit has been to intercept and convey tailwater runoff which would otherwise flow over surface lands, infiltrate, and contribute to additional subsurface groundwater flows, which would subsequently reach the Colorado River with increased salt pickup.

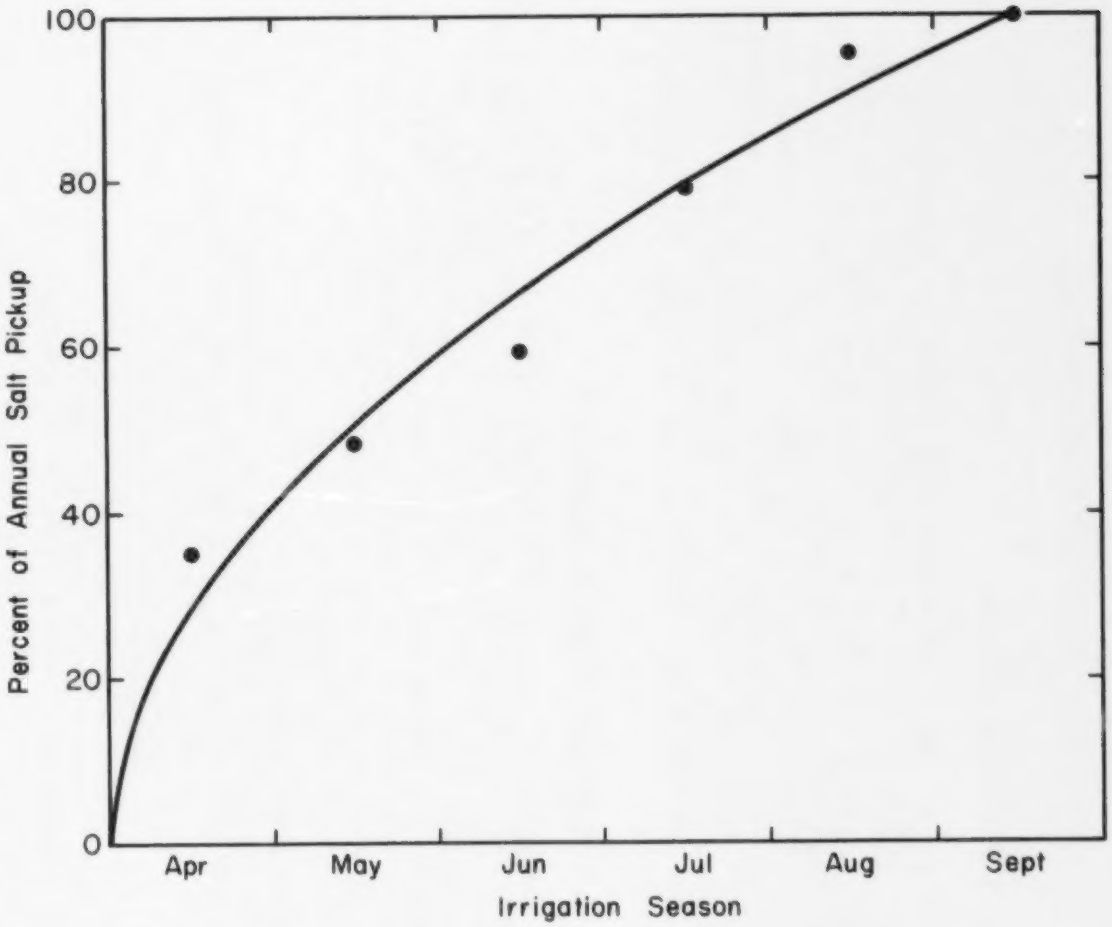


Figure 21. Seasonal distribution of salt pickup from the farms in the test area (Skogerboe et al., 1974b).

SECTION 6

IRRIGATION WATER REQUIREMENTS

COMPUTING EVAPOTRANSPIRATION

A review of the alternative approaches to estimating the volume and rates of water evaporated from wet crop and soil surfaces or transpired by the plants can be found in several literature sources (Jensen, 1973; Doorenbos and Pruitt, 1977). So far as this technology is applicable to the management of irrigation return flow quality (through irrigation scheduling), Skogerboe et al. (1974b) and Jensen (1975) are good summaries. In this section, some of this previously reported work will be repeated in order that in later paragraphs our efforts at calibrating and verifying estimating procedures will be more understandable.

Methods of Estimating Evapotranspiration

The analysis of irrigation return flows in the Grand Valley has included three principal approaches to estimating evapotranspiration: (a) the Blaney-Criddle method; (b) the Modified Jensen-Haise method; and (c) the Penman Combination method. These methods represent much of the range in sophistication available today, varying in detail from a temperature dependent analysis (Blaney-Criddle) to an analysis of energy balance and convective transport (Penman).

The Blaney-Criddle Method--

The Blaney-Criddle procedure for estimating evapotranspiration has the form (Blaney and Criddle, 1950):

$$E_t = \frac{k_t \, k_c \, t \, p}{100} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where,

E_t = monthly evapotranspiration in inches;

$$k_t = 0.0.173t - 0.314; \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

k_c = time distributed crop growth stage coefficient;

t = mean monthly temperature in °F; and

p = mean monthly percentage of annual daytime hours.

Crop curves and values for p can be found in Blaney and Criddle (1950). Estimates of E_t were originally intended on a seasonal basis, but work by numerous individuals have shortened this interval by interpolating values for p and k_c.

The Modified Jensen-Haise Method--

The Jensen-Haise procedure is a temperature and solar reduction equation adjusted for location and elevation by vapor pressure functions (Jensen and Haise, 1963):

$$E_{tp} = C_t(T - T_x)\ R_s \quad . . . . (3)$$

in which,

E_{tp} = average daily potential evapotranspiration of a well-watered alfalfa crop having 30-50 cm of top growth, mm/day;
T = mean daily temperature, °C;
R_s = total daily solar radiation in langleys multiplied by 0.0171 to get mm/day;
T_x = intercept of the temperature axis

$$= -2.5 - 0.14(e_2 - e_1)\ °C/mb - elev(m)/550. \quad . . . (4)$$

e_2, e_1 = saturation vapor pressures at the mean maximum and mean minimum temperature, respectively, for the warmest month of the year, in mb;
C_T = temperature coefficient

$$= \frac{1}{C_1 + C_2\ C_H} \quad . . . . (5)$$

$$C_1 = 38 - (2°C \times elev(m)/305) \quad . . . . (6)$$

$$C_2 = 7.6°C \quad . . . . (7)$$

$$C_H = \frac{50\ mb}{(e_2 - e_1)} \quad . . . . (8)$$

In order to relate E_{tp} to evapotranspiration values for other crops, a crop growth stage coefficient was defined,

$$k_{co} = E_t/E_{tp} \quad . . . . (9)$$

where

k_{co} = crop growth stage coefficient; and
E_t = potential evaporation for the specified crop.

Kincaid and Heerman (1974) present polynomial regression equations for k_{co} based on the table of coefficients presented by Jensen (1973).

The Penman Combination Method--

Penman (1948) first derived an equation for the evapotranspiration of a short, well-watered crop (generally assumed to be grass) based on a combination of energy balance at the crop surface and the heat-mass transfer processes due to air movements. The equation which resulted and is used today is written for alfalfa:

$$E_{tp} = [\frac{\Delta}{\Delta+\gamma} (R_n+G)+15.36 \frac{\Delta}{\Delta+\gamma}(a+bU_2)(e_z°-e_z)]\cdot 0.0171 \quad . \; . \; (10)$$

in which,

Δ = slope of the saturation vapor pressure curve at a specified temperature, d(mb)/d(°C);
γ = psychrometic constant, mb/°C;
R_n = net radiant energy, langleys/day (ly/day);
G = soil heat flux, ly/day;
U_2 = wind run at a height of 2 meters, km/day;
a,b= empirical regression coefficients requiring local calibration;
$e_z°$= saturation vapor pressure at the surface of the crop, mb; and
e_z = vapor pressure at the crop surface, mb.

The data available at most irrigated sites employing the Penman approach include solar radiation (R_s), temperature, wind, and relative humidity or dew point temperature. In order to develop the parameters for Eq. (10), a number of empirical functions can be used. In the Grand Valley, the approach that was used is described below.

Net radiation, R_n, was determined from relationships presented by both Jensen (1973) and Kincaid and Heerman (1974). This procedure begins by defining solar radiation on a clear, cloudless day by plotting a curve through the long-term maximal values:

$$R_{so} = 760 \exp-[\frac{Day - 107}{167}]^2 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (11)$$

where

R_{so} = clear day solar radiation, ly/day; and
Day 1 = March 1.

A more recent review by the writers of Eq. (11) indicates the coefficient 760 should be increased about 10 percent, but the overall effect is negligible. In a similar view, it is necessary to define the clear day net outgoing longwave radiation:

$$R_{bo} = \varepsilon' \sigma T_k^4 \quad \ldots\ldots\ldots\ldots \quad (12)$$

where

R_{bo} = net clear day outgoing longwave radiation, ly/day;

$$\varepsilon' = -0.2 + 0.261 \exp[-7.77 \times 10^{-4}(273-T_k)^2] \quad \ldots \quad (13)$$

T_k = temperature in degrees Kelvin (°C + 273)

σ = Stefan-Boltzmann constant = 11.21×10^{-8} ly/°K

Based on Eqs. (11) and (12), the longwave radiation (R_b) occurring on a particular day equals (Jensen, 1973):

$$R_b = [1.2 \frac{R_s}{R_{so}} - 0.2]\, R_{bo} \quad \ldots\ldots\ldots\ldots \quad (14)$$

and

$$R_n = (1-\alpha)R_s - R_b \quad \ldots\ldots\ldots\ldots \quad (15)$$

in which α = crop albedo (generally taken to be 0.23).

The exchange in heat from the soil is based on two assumptions: (1) the soil temperature to a depth of 2 meters varies approximately with average air temperature; and (2) the volumetric heat capacity of the soil is 0.5 cal cm^{-3} °C^{-1}. The soil heat flux, G, is then written as (Jensen, 1973):

$$G = \frac{\overline{T}_{i-1} - \overline{T}_{i+1}}{\Delta t} \times 100 \quad \ldots\ldots\ldots\ldots \quad (16)$$

where,

G = soil heat flux, ly/day;

$\overline{T}_{i-1}$ = mean temperature for the previous period, °C;

$\overline{T}_{i+1}$ = mean temperature for the following period, °C; and

Δt = days between the preceding and following periods (period interval).

Kincaid and Heermann (1974) use a comparison of current temperature with the average of the previous 3 days to calculate G for irrigation scheduling. They also presented convenient expressions for $\Delta/\Delta+\gamma$, $\gamma/\Delta+\gamma$, and e_z^o as follows:

$$\gamma/\Delta+\gamma = 0.959 - 0.0125T + 0.00004534T^2 \quad \ldots\ldots \quad (17)$$

$$\Delta/\Delta+\gamma = 1 - (\gamma/\Delta+\gamma) \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (18)$$

$$e_z^o = -0.6959 + 0.2946T - 0.005195T^2 + 89\mathrm{x}10^{-6}T^3 \; . \; (19)$$

in which T represents the mean daily temperature in °F.

The evaluation of the term ($e_z^o - e_z$) in the Penman equation can be made in several ways. For the Grand Valley studies, the following expression was used:

$$(e_z^o - e_z) = \frac{e_2^o + e_1^o}{2} - e_1^o \mathrm{\ x\ } rh \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (20)$$

in which
e_z^o, e_1^o = saturation vapor pressure at maximum and minimum daily temperatures, mb; and
rh = maximum daily relative humidity (usually taken as the 6-8 AM values) expressed as a fraction.

Calibrating Estimating Formulas

In 1974 two constant-water-table grass lysimeters one meter square in surface area were set up in the Grand Valley along with a climatic station recording precipitation, temperature, solar radiation, and relative humidity. A diagram of the lysimeters is given in Figure 22. Evans et al. (1978) presented the data collected from the lysimeters and their extension to other locally grown crops.

Blaney-Criddle Calibration--

The Blaney-Criddle equation, as described earlier, underestimates E_{tp} in the Grand Valley by approximately 40 percent. Generally, in the windy months of spring the procedure underestimates E_{tp} by as much as 50 percent, whereas later results show substantial overestimation. The calibration of Eq. (1) involved solving for the k_t term:

$$at - b = \frac{E_t \cdot 100}{p \cdot t \cdot k_c} \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (21)$$

In this case, k_t was found to be:

$$k_t = -0.002686t + 1.49 \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (22)$$

Even so, the month-to-month variations were large (i.e., equations 1 and 22 overestimate E_{tp} in May, July and September, while it underestimates the values in June and August). It should be noted that calibration of the k_t parameter over so

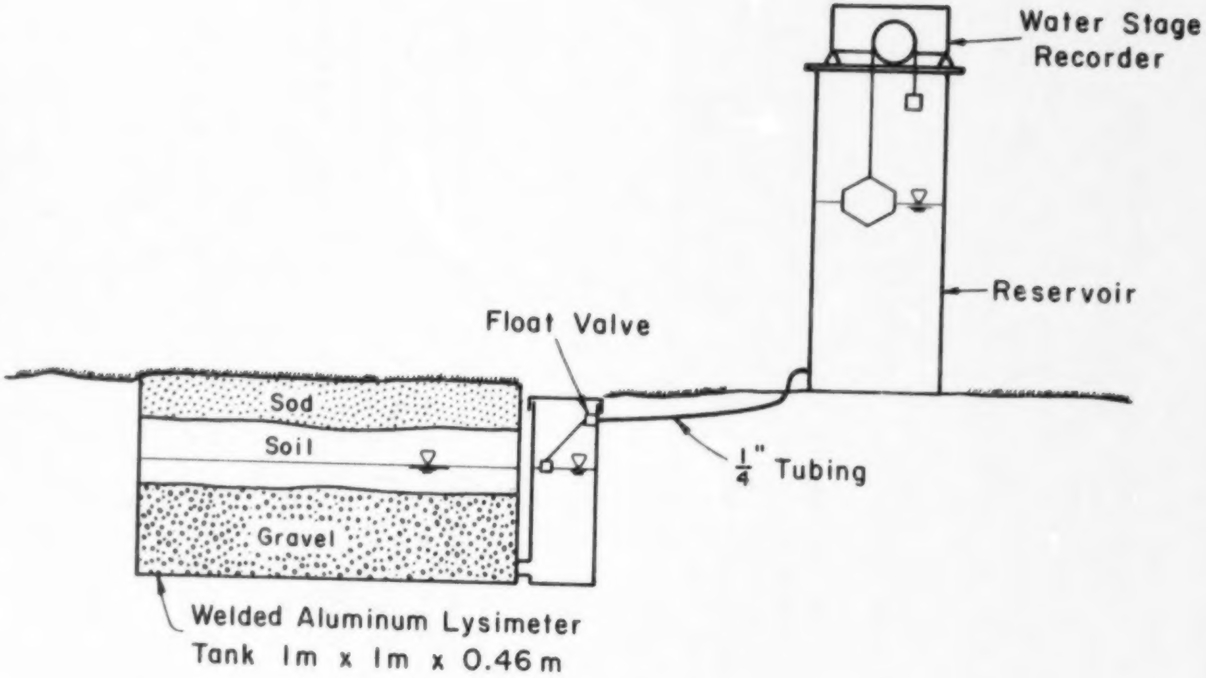

Water Stage
Recorder
Reservoir
Float Valve
Sod
Soil
Gravel
$\frac{1}{4}$" Tubing
Welded Aluminum Lysimeter
Tank 1m x 1m x 0.46 m

Figure 22. Schematic view of the constant water level tank grass lysimeter used in the Grand Valley.

short a time period does not give complete confidence in the resulting equations because temperature is only one of many climatic factors affecting evapotranspiration. A longer term analysis is needed before proposing a usable function for k_t beyond that expressed in Equation 2.

Jensen-Haise Calibration--

In the Grand Valley, the mean minimum and mean maximum temperatures at the 1480 meter elevation are 34.6°C and 18.1°C, respectively. At these temperatures, $e_2 = 55.29$ mb and $e_1 = 20.58$ mb so that $C_H = 1.44$. The data similarly result in C_T being equal to 0.0255 and $T_x = -10.05$. The Jensen-Haise equation for the Grand Valley is, therefore (multiplied by 0.0171 to yield mm/day):

$$E_{tp} = 4.36 \times 10^{-4}(T + 10.05)R_s \quad . . . . (23)$$

Equation 23 overestimates evapotranspiration as determined from the grass lysimeters (and divided by 0.87) by 4 percent to 5 percent over the accumulated irrigation season. However, during the windy periods of May and June, Equation 23 can underestimate E_{tp} by about 10-15 percent. By solving for C_T and T_x and correlating with the lysimeter data, Equation 23 was slightly modified as indicated below:

$$E_{tp} = 4.75 \times 10^{-4}(T + 9.646)R_s \quad . . . . (24)$$

Penman Calculation--

The Penman equation has several regression formulas implied in its form as listed in Equation 10. An evaluation of each of these was made, but the only effective correlation was between the wind term coefficients, a and b. Interestingly enough, the values determined for alfalfa (a = 0.90 and b = 0.0062) are not significantly different from the values Penman originally suggested for grass (Jensen, 1973). The resulting Penman formula for alfalfa (E_{tp}) is:

$$E_{tp} = 0.0171[C_1(R_n+G)+C_2(0.9+0.0062\ U_2)(e_z^o-e_z)] \quad . (25)$$

Comparison of Methods

The mean monthly measured values of the grass lysimeter evapotranspiration are plotted against both the calibrated and original Blaney-Criddle relationships in Figure 23. These data were collected in 1975. The other years do not differ markedly, however. The revised function for k_t allows a substantially better monthly estimate of consumptive use than the version suggested by Blaney and Criddle (1950). In fact, over the season

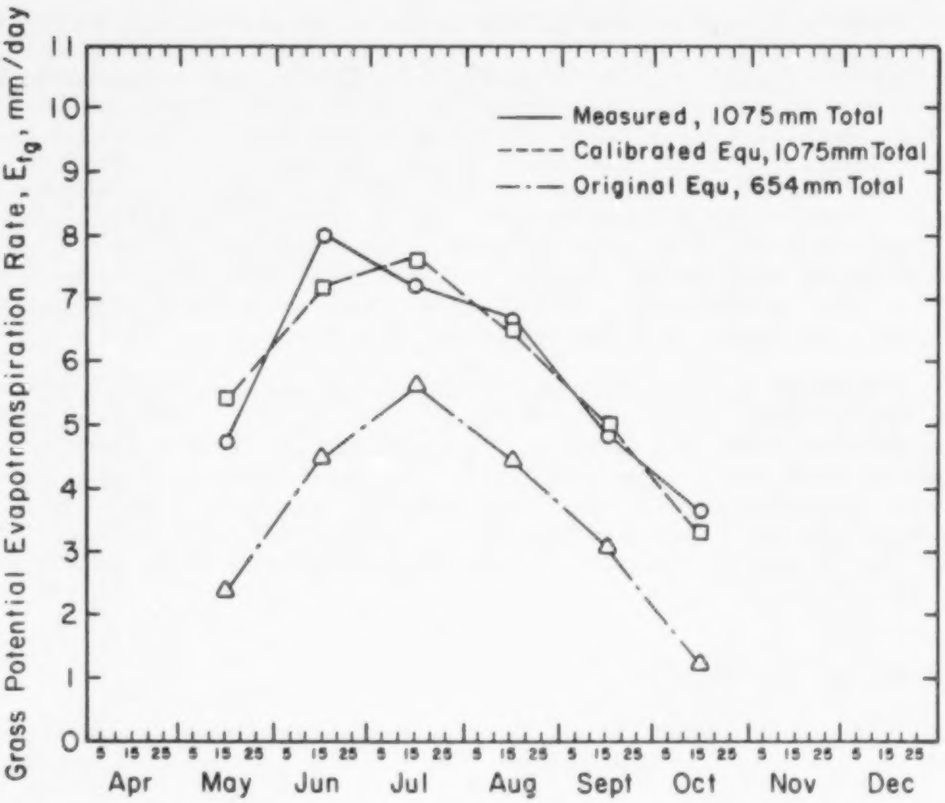


Figure 23. Comparison of lysimeter data with the Blaney-Criddle estimates for well-watered grass in 1975.

the measured and predicted (by the adjusted equation) are identical. The Blaney-Criddle approach is satisfactory for time periods greater than or equal to one month, but not the daily or weekly periods needed for irrigation scheduling. It is also obvious that application of the original Blaney-Criddle approach can lead to significant errors if the method is not locally calibrated.

Figure 24 shows the comparison of measured and calculated E_{tp} values during the 1975 irrigation season in Grand Valley when the Jensen-Haise method is applied. The error introduced by simply using the reported function with the altitude correction is too small to be significant, although about a 4-5 percent improvement was achieved with local calibration. The Jensen-Haise method is often used in conjunction with the Penman equation in many irrigation scheduling services, primarily from July on when wind is less significant. The largest error in the time distributed estimates (5-6 day intervals) was less than 2 mm per day in the latter part of the Grand Valley's 1975 irrigation season. In June, a 5 mm error is noticeable.

Although the Penman equation shows more seasonal error than the Jensen-Haise approach (Figure 25), it follows the lysimeter data better over the season. In evaluating these results, it appears that time intervals less than 3-5 days are not justified by the sensitivity of the approaches. In fact, the correlation between measured and predicted values on a daily basis was less than 70 percent, whereas it was approximately 90 percent for 5-6 day periods.

IRRIGATION SCHEDULING

Irrigation scheduling in its simplest form of predicting when to irrigate is practiced continually by all irrigators. The scheduling criteria are often "judgment" oriented but are generally adequate. Modern scientific irrigation scheduling services utilize soil moisture budgeting procedures to not only predict the timing of the next irrigation, but also the necessary quantities of irrigation water to be applied.

With various alternatives at each step, the irrigation scheduling operation is basically a two step process. First, the soil moisture status at the present must be updated from the last date when it was known. This procedure involves adjusting the potential evapotranspiration calculated from the Penman or Jensen-Haise equations for crop, growth stage, and soil moisture stress and including irrigation and precipitation in the update interval. Because the soil moisture is being updated rather than predicted, actual field and climatic data are used. The second step is to determine the date of the next required irrigation and

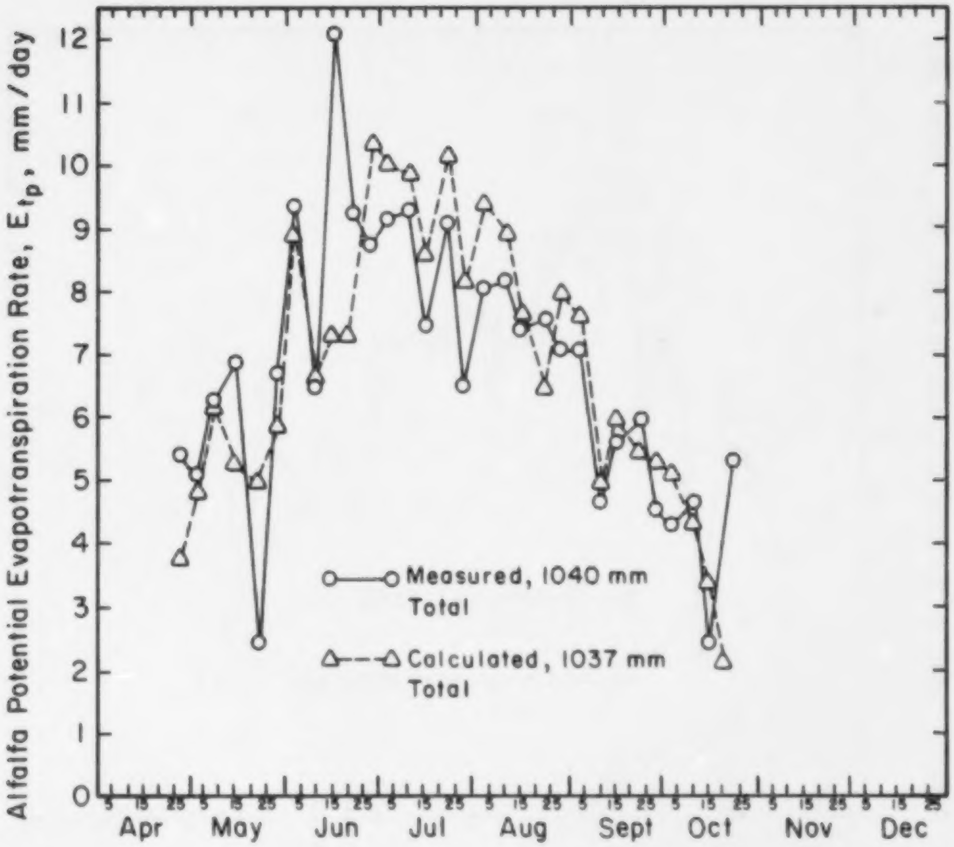


Figure 24. Comparison of lysimeter data with the Jensen-Haise estimate for alfalfa in 1975.

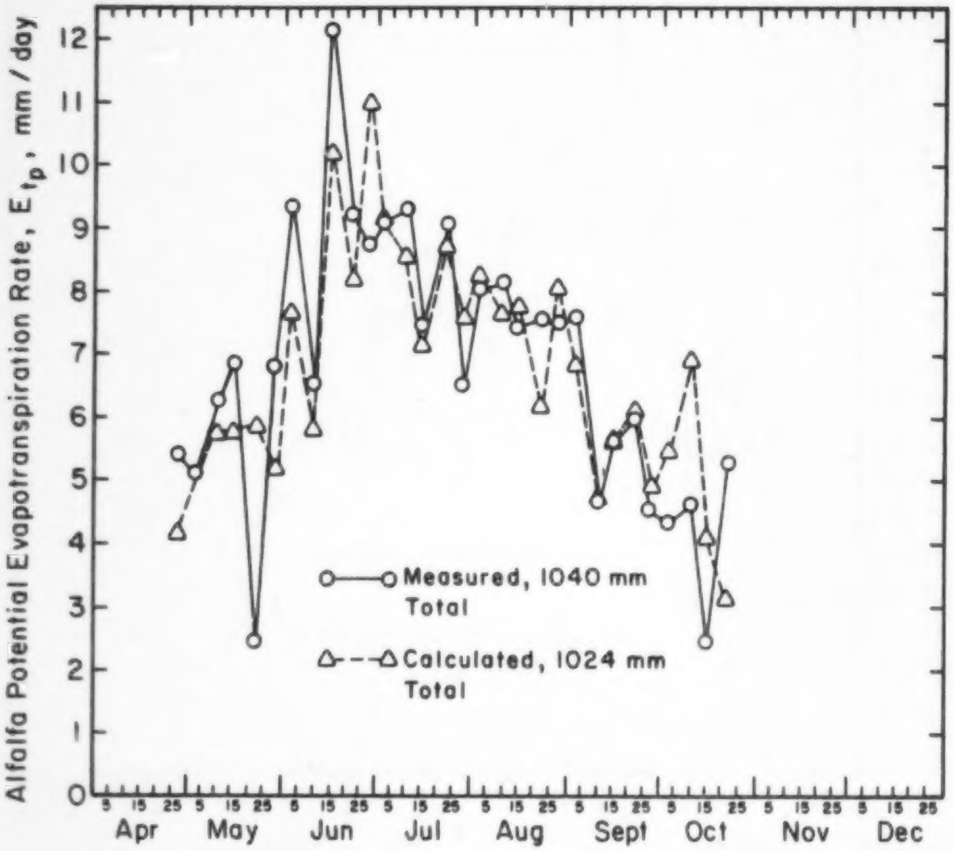


Figure 25. Comparison of lysimeter data and the Penman equation estimate for alfalfa in 1975.

the amount it should involve. This analysis is based on anticipated climatic and crop water use data.

Updating the Soil Moisture Status

In general, the availability of moisture in a crop root zone must be periodically calculated rather than measured to insure a reliable estimate of the depth and timing of future irrigations. Measurements, of course, are preferable but cannot be made with sufficient frequency. Consequently, the soil moisture storage at the present is determined by starting at the beginning of the update period and sequentially deducting the evapotranspiration from soil moisture. This procedure assumes the conditions at the beginning of the period are known.

The first step in updating the existing soil moisture storage is the calculation of actual evapotranspiration. Beginning with the potential evapotranspiration of alfalfa, E_{tp} (from Equations 23 and 24), a crop coefficient k_{co} is defined such that:

$$E_t = k_{co} E_{tp} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (26)$$

where E_t is the potential evapotranspiration of the particular crop at the point in time encompassed by the update period. The value of E_t depends also on the availability of soil moisture and decreases as the depletion increases. Jensen (1973) and Kincaid and Heerman (1974) define a stress coefficient:

$$k_s = \frac{\log[1 + 100(1 - D_p/D_T)]}{\log 101} \quad \ldots\ldots\ldots\ldots \quad (27)$$

in which,

k_s = stress coefficient;

D_p = actual soil moisture depletion, in mm; and

D_T = field capacity, in mm.

Whenever a rain or an irrigation occurs, the actual evapotranspiration is actually increased somewhat due to free water at the crop and soil surface. To account for this, an additional quantity of evapotranspiration is added to E_t as follows:

$$E_{tr} = k_r(0.9 - k_{co}k_s)\ E_{tp} \quad \ldots\ldots\ldots\ldots\ldots \quad (28)$$

where

E_{tr} = added evapotranspiration due to rain or irrigation, mm/day;

k_r = 0.8 for first day following rain or irrigation;
= 0.5 for second day;
= 0.3 for third day; and
= 0.0 for other days.

If the value of $k_{co}k_s$ is greater than 0.9, E_{tr} is set equal to zero. Thus, the actual evapotranspiration of a given day is:

$$E_t = [k_{co}k_s + k_r(0.9 - k_{co}k_s)]E_{tp} \quad \text{. . . . . (29)}$$

In order to compute the value of the stress coefficient, k_s, the values of soil moisture depletion must also be known. This involves two factors. First, as the roots grow in the early season, more and more available soil moisture is added to the system:

$$D_T(t) = (MC)[RD_i + (RD_m - RD_i)\cdot r] \quad \text{. . . . . (30)}$$

in which,

$D_T(t)$ = field capacity of the root zone with time, mm;

MC = moisture content at field capacity, mm/m;

RD_i = initial rooting depth, m;

RD_m = maximum rooting depth, m; and

r = interval of the planting date to present divided by the time between planting date and full crop cover.

Then, the soil moisture depletion on a day i is written,

$$D_p(t) = D_p(t-1) + E_t - R_i \quad \text{. . . . . (31)}$$

where,

$D_p(t)$ = soil moisture depletion, mm; and

R_i = rainfall or irrigation on the day.

The value of D_p substituted into Equation 27 for a day i is usually the value $D_p(i-1)$.

Predicting the Next Irrigation

Once the soil moisture system has been updated to the present, and assuming the soil moisture has not already reached the level when an irrigation should be initiated, the next step is to determine when and how much to irrigate. Because real time climatic data or soil measurement are not yet available, the root zone budgets must be projected into the future until the soil moisture level at which an irrigation should occur is determined. These calculations occur in the same order as the updating analyses except the daily evapotranspiration potential (E_{tp}) is replaced by the long term average E_{ta}. In the Grand Valley, for example, the calibrated Penman and Jensen-Haise equations were applied using mean climatological data resulting in the relationship:

$$E_{ta} = 8.51 \exp-[(\mathrm{Day}-137)/\Delta \mathrm{Day}]^2 \quad (32)$$

in which,

E_{ta} = mean potential values for E_{tp}, mm/day;

Day = present modified julian date (Mar. 1 = 1); and

ΔDay = 90 if Day $\geq$ 137 and 120 if Day < 137.

When the date of the next irrigation is determined, the amount to apply at that point will equal the allowable depletion (depletion when irrigation is to be initiated) divided by the irrigation application efficiency. The application efficiency depends on the irrigation method and the practices followed by the irrigator. This latter aspect will be covered in the following sections.

Implementing Irrigation Scheduling

There have been numerous irrigation scheduling studies reported in the literature. The necessary parts of a scheduling program in a salinity control effort are discussed by Skogerboe et al. (1974b) and will not be repeated here. One aspect, however, should be noted in this section since it will become important in the discussion of irrigation uniformities in later sections.

An irrigator does not wish to see parts of his field "burning" for lack of soil moisture. Consequently, the field is usually irrigated until the least watered area is adequately refilled. An irrigation scheduling program which monitors soil moisture to update and monitor computer simulations will overestimate the interval between irrigations (as decided by irrigators) and underestimate the time water needs to be applied to the field if it evaluates soil moisture status at a location other than at the minimum irrigated area. For surface irrigated systems, soil moisture should be monitored near the end of the fields, whereas pressure irrigated systems are least watered in the center of the lateral emission points.

SECTION 7

GENERAL CONSIDERATIONS IN IRRIGATION

Approximately one-fourth of the total cultivated land in the world, which is about 162 million hectares are presently irrigated (Israelsen and Hansen, 1967). Historically, civilizations have been dependent on the development of irrigated agriculture; and in many of these same areas today, irrigation still provides the agrarian basis of society.

However, when the constraints of the entire soil-water-plant relationships are ignored either through ignorance or lack of planning, an irrigated agrarian industry will eventually disappear. A good example is the ancient civilization of Mesopotamia which flourished in the Tigris-Euphrates Valley 6,000 years ago (Kang, 1972). In 2,000 years the soil became so saline due to poor irrigation practices and lack of drainage that it has not recovered to this day. It had been estimated that Mesopotamia supported as many as 25 million persons. Iraq, which presently occupies much of this same area, today has a population near 10 million. In fact, the tax records from Mesopotamia show that barley yields were about 2500 liters/ha, whereas present yields in this area are only one quarter to one half of this value (Kovda et al., 1973).

When a reliable and suitable supply of water becomes available for agriculture in a previously dry area, it immediately results in vast improvements in agricultural production and assures economic returns to the grower. However, in time, without proper agronomic practices accompanying the irrigation, these lands will become unproductive and barren. These "proper" agronomic practices can include drainage, fertilization, crop rotation, soil reclamation and management, erosion control, and the selection of crops best suited to local conditions. All of these considerations must be integrated into the practice of irrigation to realize the full potential of irrigated agriculture, which can be many times the initial advantage of irrigation.

OBJECTIVES OF IRRIGATION

Irrigation in arid areas of the world has two primary objectives: (a) to supply the essential moisture for plant growth; and (b) to leach (wash out) or dilute chemical salts in the soil. Irrigation water has a side benefit, cooling the soil and the atmosphere thereby providing a more favorable environment for plant growth. Irrigation supplements the supply of water received from precipitation and other types of atmospheric water, flood waters, and groundwater.

The first objective of supplying the necessary moisture can be accomplished in several ways. However, regardless of the method used, the purpose of irrigation is to periodically replenish the "soil moisture reservoir" of the plant's root zone. This reservoir is depleted by the consumptive demands of the plant. The only existing method of irrigation which is an exception to this rule is drip or trickle irrigation, which starts with a full root zone reservoir and directly replaces the water consumed by the plant on an almost daily basis, instead of waiting until the available soil moisture has been depleted by a specified value (usually 50 percent to 70 percent of the difference in soil moisture holding capacity of the root zone between field capacity and wilting point).

Salts are contributed to water supplies by two main processes: salt concentrating and salt loading. Salt concentration effects are due to the removal of water by the consumptive use of crops and other natural vegetation, the interbasin export of high-quality water, and the evaporation from the water surfaces of streams and lakes. As this "pure" water is depleted from the system, the mineral constituents left behind increase the concentration in the remaining flow. Salts contributed by salt loading are due to the chemical weathering of soil and substrata by irrigation water and natural subsurface flows. Salt loading is also caused by excessive fertilizer applications, municipal and industrial wastes, and point sources such as mineral springs, flowing brine wells, and geysers.

If the salts left behind in the root zone as a result of evapotranspiration are not periodically leached from the crop root zone, the land will become unproductive. This second objective of irrigation is very important and often will occur naturally during an irrigation. However, the water which passes through the root zone carrying the excess salts is often severely restricted from further travel by subsurface conditions. When this occurs, this leachate will eventually build up into the root zone causing high salinity levels and poor aeration (waterlogging). This phenomenon, in fact, has been the downfall of many great historic civilizations. Today, however, this waterlogging problem can be alleviated with proper drainage control measures or improved irrigation water management practices. For this reason, drainage should be considered as an integral part of any irrigation development project and not as an afterthought.

Another serious problem of irrigated agriculture is soil erosion, where top soil and soil nutrients are carried by tailwater into the reservoirs, canals, and laterals of downstream users. Siltation reduces the capacities of drainage and irrigation channels, resulting in costly large-scale maintenance programs and the installation of expensive structures for its removal. The useful lifetime of dams and reservoirs is often computed in terms of the rate of sedimentation.

SOIL-WATER-PLANT RELATIONSHIPS

Soil, water, and plant relationships of particular importance to irrigated agriculture include: (a) the capacity of the soil to hold water and still be well drained; (b) the flow characteristics of water in the soils; (c) the physical properties of the soil matrix including the organic matter content, soil depth, soil texture, and soil structure; and (d) soil chemical properties including the translocation and concentration of soluble salts and nutrients due to the movement, use, and evaporation of the soil water. Knowledge of all these relationships and how they influence each other is critical to all who desire to improve irrigation practices and obtain the best, most efficient use of water.

Soil Moisture

If there is either excessive water (waterlogging), or insufficient water, crop growth will be retarded. While irrigation is an artificial means of adding to the available soil moisture to prevent moisture deficiencies, poor irrigation practices create the waterlogging problem. As commonly defined, the available moisture is that which is held in the soils at a negative apparent pressure range from one-third bar (field capacity) to 15 bars (permanent wilting point). However, the available moisture content within this pressure range will vary from 25 cm per meter of soil depth (3 in/ft) for some silty loams to as low as 6 cm per meter of soil depth (0.75 in/ft) for some sandy soils. As a consequence, the soil type can greatly influence irrigation management practices. The percentage of water at the permanent wilting point is usually about half of that at field capacity, but still much greater than the water content of air dried soil.

When the available soil moisture is in the range below a 50 percent to 70 percent moisture depletion and approaching the permanent wilting point, the limited water supply will play an important role in retarding plant growth. When a plant becomes "stressed" due to the influence of these soil water deficits, there are several changes in the physiological processes of the plant. If these stresses occur during a critical stage such as flowering or fruiting (these "critical" stage(s) will vary from plant species to plant species), the crop yields can be severely reduced. If the plant is stressed below the permanent wilting point, it will probably not recover.

Soil Hydraulic Characteristics

A property of soils which is extremely important to irrigated agriculture is the rate of infiltration or the time rate at which water will percolate into the soil. It is influenced by chemical and physical soil properties and the hydraulic gradient. The configuration of the soil surface (i.e., furrows or borders), the slope, the roughness, and type of vegetative cover will also influence infiltration. Whenever the surface configuration influences the rate of water entry into the soil, the term "intake rate" is used instead of the "infiltration rate."

Infiltration rates will vary from being relatively high at the start of an irrigation to a much lower value at the end. It can also vary throughout the irrigation season as is the case in the Grand Valley (see Figure 20, Section 5). Water standing on coarse or sandy soils will infiltrate rapidly, but water on a very fine-textured clay soil may often stand for days, and the evaporation rate can be higher than the infiltration rate. The term cumulative infiltration (or depth of application), which accounts for these time variations, is used to define the total amount of water delivered to the root zone during an irrigation. The depth of application is dependent on the length of run, total time of application (total volume applied), and the volume rate of inflow.

Soil Physical Properties

The soil matrix serves several very valuable functions, not the least of which is serving as a foundation to hold the plants upright. It must also furnish nutrients and provide a good balance between areation and available moisture content.

Soil texture and structure influences the intermolecular forces and "suctions" of water in unsaturated soils. These forces can be quite substantial and include the capillarity and attractive forces resulting from the close contact of soil particles. Soil texture, primarily soil structure, greatly influences the distribution of pore sizes, and thereby the permeability of soils to air, water, and roots which is as important to crop growth as is an adequate supply of nutrients. In fact, the entire soil-water-plant system is so interrelated that the failure or lack of one component can cancel the combined benefits of all the others.

The depth of soil is important because it establishes the amount of water and nutrients which can be stored, as well as the physical limits of the root zone. A deep soil is necessary to have a well-drained soil. Shallow soils directly influence the rate and depth of root growth.

Irrigation practices are influenced by the degree of root proliferation since the water supply available to the plant is limited to the distribution of and soil volume explored in the crop's root system. Different crops have different root growth patterns, hence, different moisture extraction patterns. Obviously, a shallow-rooted crop will require more frequent irrigations than a deep-wide-rooted crop, given the same soil moisture holding capacity.

Soil Chemical Properties

The chemical properties of soils can greatly influence the irrigability of the soil by affecting the hydraulic characteristics and the suitability of the soil for crop production. Soils having an excess of soluble salts are designated as saline soils, and, if the soil has an excess of exchangeable sodium, it is termed a sodic soil. Sodic soils tend to have very poor soil structure due to swelling or dispersion properties which tend to greatly reduce pore size distribution. This has an enormous effect on the hydraulic properties of the soil. For example, the hydraulic conductivity of a soil can change as much as three orders of magnitude when the sodium adsorption ration (SAR) is reduced from a value of 20 to 1, holding all other soil properties constant (Dane, 1976).

Excess soil salinity will delay or prevent crop germination and can substantially reduce the amount and rate of plant growth because of the high osmotic pressures which develop between the soil water solution and the plant. These pressures, which appear to be independent of the type of salts present, greatly impair the plant's ability to absorb water. In addition, some adverse effects due to salinity can include nutritional imbalances or toxicities caused by specific ions (i.e., boron which is toxic in very small quantities). In sufficient concentrations, even beneficial salts (fertilizers such as potassium nitrate) can become toxic to plants.

In addition to the soil chemical characteristics mentioned above, the soil must also have an adequate supply of available plant nutrients. Many chemical elements are essential for plant growth and are necessary to obtain large and satisfactory crop yields. These include calcium, carbon, hydrogen, iron, magnesium, nitrogen, oxygen, potassium, phosphorus, sulfur, and many other trace elements depending on the type of crop. The availability of these nutrients to the plant depends to a large extent upon the moisture content of the soil.

Bacterial activity is also an important part of the soil-water-plant relationship because this action will often convert nitrogen to a usable form (nitrogen-fixing). Bacterial action also breaks down organic matter and converts other chemical compounds into forms usable by the plants. Soil moisture content, soil structure, and soil aeration directly influence bacterial activity.

AGRICULTURAL INPUTS

The optimal objective of proper irrigation management is to maximize efficiencies and minimize the labor and capital requirements of that particular irrigation system as much as possible; and, at the same time, maintain a favorable growing environment for the plant in order to maximize yields. Some managerial inputs are dependent on the type of irrigation system and the design of the system. For example, the degree of automation, the type of system (sprinklers, trickle, or conventional surface irrigation), the reuse of field tailwater, soil type, topography variations in a field or farm, and the existence and location of management tools such as flow measurement and water control structures can influence the managerial decision making processes.

However, management decisions which are common to all systems, regardless of the types, are the frequency of irrigation, depth of water to be applied, and measures to increase the uniformity of applications such as land leveling or shaping. In addition, individual systems can be manipulated to greatly increase application efficiencies. For example, in furrow irrigation some growers will use two siphon tubes per furrow at the start of irrigation (wetting phase), and when the water has reached the end of the row, one tube is removed (infiltration stage). This increases the efficiency by minimizing field tailwater runoff; however, it requires an additional labor input. This method of irrigation is called cutback furrow irrigation and can be easily automated (Evans, 1977).

In recent years, irrigation scheduling services have aided the farm manager with decisions on how much to apply and how frequently. Irrigation practices such as preirrigations before planting, irrigating plants up after planting, or the length of time per set, are managerial inputs which influence water use efficiency over the season.

CRITERIA FOR SELECTING METHODS OF IRRIGATION

There are a large number of considerations which must be taken into account in the selection of an irrigation system. These factors will vary in importance from location to location and crop to crop, and a detailed explanation of all considerations is beyond the scope of this report. Briefly stated, these considerations include the compatibility of the system with other agricultural operations, economic factors, topographic limitations, soil properties and many agronomic and external influences.

Compatibility

The irrigation system for a field or a farm must be compatible with other existing farm operations such as land preparation, cultivation, and harvesting practices. For instance, the use of the more efficient, large machinery requires longer and wider fields with wider borders or perhaps even removable irrigation systems.

Economic Considerations

The type of irrigation system selected is also an economic decision. Some types of sprinkler systems have high per acre costs and their use is therefore limited to high value crops. Other systems have high labor requirements, and some have fairly high operating costs. Also, some systems have limitations with respect to the type of soil or the topography on which they can be used. The expected life of the system, fixed costs, and annual operating costs (energy, depreciation, taxes, etc.) should also be included in the analysis when selecting an irrigation system.

The type and relative cost of power, and availability and quality of labor, also enters into the type of system to be used. The type of power could be electricity (phase, voltage, and horsepower limitations), or internal combustion engine (fuel type, cost and availability). These factors and others determine the cost of the water supply.

Topographic Limitations

Restrictions on irrigation system selection due to topography include groundwater levels , the location and relative elevation of the water source, field boundaries, acreage in each field, the location of roads and natural gas lines, electricity and water lines and other obstructions, the shape of the field, and the field slope (which can vary dramatically over a field). Field surface conditions such as relative roughness and gullies should also be considered.

The slope of the land is very important. Some types of sprinklers can operate on slopes up to 20 percent or more, but furrow or graded border irrigation is usually limited to a maximum slope of around 2 to 6 percent. Trickle irrigation can be used on slopes up to 60 percent or more.

The shape of a field also determines the type of system. For instance, level borders, furrows, hand-move or solid-set sprinklers, subsurface, contour ditch, or trickle irrigation systems can be adjusted to fit almost any field shape; whereas, a center-pivot sprinkler must have approximately round (or elliptical) shaped fields. For a side-roll sprinkler, level furrow, graded border or contour furrow, the field should be approximately rectangular in shape.

Soil Characteristics

The soil type, soil moisture holding capacity, the intake rate, and effective soil depth are also criteria which enter into the type of system selected. For example, sandy soils have a high intake rate and will accept high volume sprinklers which would be unacceptable on a tight clay soil.

The moisture holding capacity will influence the size of the irrigation sets and frequency of irrigations as evidenced by a sandy soil with low moisture holding capability which requires frequent, light applications of water. A center-pivot or side-roll sprinkler or even a trickle irrigation system would perform satisfactorily in this case.

Other Considerations

Most surface systems, drip irrigation, and some sprinkler systems can be used for fertigation (fertilizing through the system) and chemigation, as well as the land application of municipal and animal wastes. However, there exist advantages as well as limitations on all systems which should be understood before implementation.

Some sprinkler systems can be used for frost and freeze protection and for cooling of crops. Such systems are relatively expensive and are usually limited to high value crops such as vegetables, vineyards, and orchards. With sprinklers, the height of crop can be a significant factor for uniform application since the sprinklers should generally be above the crops.

External Influences

At times, conditions external to agriculture can influence the type of system selected. For example, an underground pipeline might be required by municipal ordinances, safety and/or aesthetics if the delivery system passes through an urban area. Other considerations might include the quality of irrigation return flows and the quality of incoming water. Also, irrigation efficiencies might have to be maintained at specified levels as a result of litigation.

IRRIGATION BENEFITS

In 1976 there was almost 23 million hectares (57 million acres) of irrigated land in the United States, a 4.4 percent increase over 1975 (1975 had a 2.5 percent increase over 1974) (Irrigation Journal, 1976). Most of this increase is occurring in the Midwest and Southeast to supplement natural rainfall. Irrigation at the optimal time in these areas can increase corn yields by 50 bushels per acre (2,000 kg/hectare) and 10 to 20 bushels per acre (430 to 860 kg/hectare) for soybeans (Irrigation Age, 1977). These production increases can be obtained by the installation of a properly designed and operated irrigation system.

In 1967, the President's Panel on World Food Supply estimated that only 44 percent of the potential arable lands in the world are under cultivation (President's Science Advisory Committee, 1967). If this land will be put into production, it will be largely the result of irrigation. Also, it is interesting to note that while only approximately 10 percent of the United States cropland is irrigated, more than 25 percent of the annual agricultural production is credited to this acreage.

As mentioned above, irrigation benefits are derived from minimizing plant moisture stress resulting from long or short duration droughts which occur even in areas where the annual precipitation is greater than the evapotranspiration. In short, irrigation reduces risk. This is especially true in arid areas such as the Grand Valley, where irrigation can literally turn a desert into an oasis.

Due to the increased production capabilities and the reduced risk potential of irrigated land, land values also appreciate. Land which is worth as little as $25-50 per acre ($60-120/hectare) without irrigation can be worth as much as $3,000-5,000 per acre ($7,200-12,000/hectare) with irrigation.

A well-designed irrigation system combined with proper soil and water management can often improve the quality of the soil as compared with its natural condition. For example, in most soils, the organic matter from decaying roots and mulches can increase the moisture holding capacity. In addition, irrigation can leach naturally saline soils to levels where large crop yields can be obtained.

SECTION 8

FURROW IRRIGATION

DESCRIPTION OF FURROW IRRIGATION

Furrow irrigation is a method of water application accomplished by diverting flows into small channels which traverse the field slope. In irrigated fields, these closely spaced channels are referred to as furrows, rills, creases, or corrugations. As the irrigation water flows in the furrows, the infiltration into the bottom and sides of the furrow is redistributed in the crop root zone for later consumptive utilization.

Efficient furrow irrigation requires that the inlet discharge and the duration of the irrigation be carefully coordinated with the field slope, furrow geometry, infiltration capacity of the soil, and the soil moisture holding characteristics. Crops which are subject to crown or stem injury if covered with water are often irrigated by furrows. This method is also well suited for crops which are planted and harvested in rows. The two-dimensional soil moisture movement condition is advantageous in not only minimizing the wetted surface area but also in the movement of fertilizers and pesticides toward the central root zone. The furrows are often used by irrigators in controlling the distribution of water over a field that is not uniformly graded.

The driving force for furrow irrigation is gravity, but the subsequent redistribution of soil moisture and evapotranspiration are functions of many soil-plant-atmospheric parameters. The water application itself, however, can be divided into three phases: (a) advance; (b) wetting; and (c) recession. For the normal practice of irrigating when the soil moisture reservoir has been depleted 50-75 percent, the recession phase is comparatively insignificant (Fok and Bishop, 1965). Infiltration at a specific point along the furrow begins at the moment the advancing water front reaches the point (advance phase) and continues as long as water remains in the furrow (wetting phase). When the discharge at the head of the furrow is terminated, the flow recedes down the field until reaching the end (recession phase).

Because irrigation with furrows is a widely used method of applying water to crops, the evaluation of the technique has been detailed by a number of investigators. The results of many of these studies, however, employ different assumptions because of the difficulties in interrelating the surface hydraulics and intake phenomena of the soil. Two basic mathematical approaches have emerged. The first is the hydrodynamic approach using continuity of mass and momentum to predict the advance-recession phases (assuming the infiltration characteristics are known). The second is the volume balance or kinetic approach. In general, the hydrodynamic approach is too time consuming and complex for generating a sufficient number of solutions to be practical. Also, the large spatial variability in soil and furrow properties render a totally theoretical description somewhat out of scope with actual field conditions. The volume balance approach, however, is not only simple to solve but also is based on easily measured field data. The literature describing the volume balance approach is very large and has been well summarized by Gerards (1978) and Karmeli et al. (1978). In this report, a summary of their works will be utilized as a basis of explanation and the more interested reader is directed to the original references for more explicit development.

BASIC FURROW HYDRAULICS

The evaluation of a furrow irrigation system involves a number of alternative approaches as noted earlier. For the purpose of this report the primary analysis will be based on the information collected on a field scale and the subsequent use of these data in the evaluation. The problem is two-fold. In the initial stages of design or evaluation, the first investigative efforts are oriented toward definition of the infiltration relationships. Later, with a knowledge of intake characteristics, the advance and uniformities are predicted.

Field Evaluation of Infiltration

Infiltration of water into the bottom and sides of a furrow is a two-dimensional process, the magnitude of which depends on depth of flow, furrow shape, and type of soil. Therefore, accurate information regarding infiltration characteristics may be obtained under actual flowing conditions or using a number of available on-site measurement techniques (blocked-furrow infiltrometers, inflow-outflow measurements, and cylinder infiltrometers). There are limitations associated with each procedure which may be identified.

The only technique using flowing conditions is known as infiltration determination based on rate-of-advance data. This approach is based on the principle of kinematics or volume-balance and requires accurate knowledge of the water introduced at the head of the furrow (V_q) and the volume of storage in the furrow at any time (V_s).

The primary element in surface irrigation evaluations is definition of soil intake or infiltration rates. Many empirical equations have been proposed, but the most commonly employed is the relationship introduced by Kostiakov (1932):

$$i = at^b \quad . . . . (33)$$

where,
i = infiltration rate in cm/min;
t = interval since infiltration began, in minutes; and
a,b = empirical regression coefficients.

Integrating Equation 33 over the irrigation interval yields:

$$I = \frac{a}{b+1}\, t^{b+1} = At^B \quad . . . . (34)$$

in which I is the cumulative soil infiltration in centimeters.

Because the intake opportunity time varies in a field due to the time required for water to reach a point, the infiltrated depth over a field's length will also vary. Thus, if t_x is the time required for the water to advance to the distance x and t_ℓ is the total time water is introduced into the field, then Equation 34 should be written:

$$I = A(t_\ell - t_x)^B \quad . . . . (34a)$$

A commonly employed function expressing the relationship between the advance rate and time is:

$$x = pt_x^r \quad . . . . (35)$$

where,
x = the distance along the flow path, in meters (m);
t = time to advance x meters, in minutes; and
p,r = empirical regression coefficients.

Actually, the parameter r can be approximated without field data if the infiltration exponent, B, is known (Fok and Bishop, 1965):

$$r = \exp(-0.6B) \quad . . . . (36)$$

Generally, however, r is determined by field data enroute to defining B. Because equation 35 is an exponential function, the slope r can be determined by knowing two points on the curve, say the time required to reach the end of the field, t_L, and the time necessary to advance one-half the field length, $0.5t_L$,

$$r = 0.69/\ln T \quad \ldots\ldots\ldots\ldots \quad (37)$$

in which:

$$T = t_L/t_{0.5L} \quad \ldots\ldots\ldots\ldots \quad (38)$$

Work reported by a number of investigators suggests that r is primarily dependent on the infiltration rate slope b (or B) as suggested by Equation 36. The parameter p, however, depends on the inflow, slope, roughness, and furrow geometry. Data have been reported which tend to substantiate these conclusions, but a well verified general predictive capability for p has not been published so far as the writers now know. Consequently, values for p must be determined for each irrigation test.

The volume of water infiltrated into the soil per unit width after the inflow has proceeded to some time is written:

$$V_\ell = 10^{-2} \int_0^\ell I \, dx \quad \ldots\ldots\ldots\ldots \quad (39a)$$

Substituting the expression for I (Equation 34) into Equation 39a yields

$$V_\ell = 10^{-2} \cdot A \int_0^\ell (t_\ell - t_x)^B \, dx \quad \ldots\ldots\ldots\ldots \quad (39b)$$

in which,

V_ℓ = total infiltrated volume into the wetted furrow length ℓ after t_ℓ minutes, m^3/m;

ℓ = length of furrow wetted as determined by equation 35, in meters; and

t_ℓ = total time water was introduced into the furrow, in minutes.

Noting that the limits of integration in Equation 39b must be changed,

$$dx = \left(\frac{\partial x}{\partial t_x}\right) dt_x = r \cdot p \cdot t_x^{r-1} \, dt_x \quad \ldots\ldots\ldots\ldots \quad (40a)$$

$$\begin{array}{ll} \ell = 0 \, , & t_\ell = 0 \\ \ell = \ell \, , & t_\ell = t_\ell \end{array} \quad \ldots\ldots\ldots\ldots \quad (40b)$$

$$V_\ell = 10^{-2} \cdot A \cdot r \cdot p \int_0^{t_\ell} (t_\ell - t_x)^B \, t_x^{r-1} \, dt_x \quad \ldots\ldots \quad (40c)$$

The solution to the integral in Equation 40c can be found by modifying the structure somewhat. Specifically, let,

$$t_\ell = t_x / t_\ell \quad \ldots\ldots \quad (41a)$$

so that by dividing terms by t_ℓ and rearranging,

$$V_\ell = 10^{-2} \cdot A \cdot r \cdot p \cdot t_\ell^{B+r} \int_0^1 (1-t)^B \, t^{r-1} \, dt \quad \ldots\ldots \quad (41b)$$

The solution of Equation 41b can be found in any standard table for definite integrals and equals,

$$V_\ell = 10^{-2} \cdot A \cdot p \cdot t_\ell^{B+r} \cdot r \cdot \beta \, (B+1, r) \ldots\ldots \quad (42)$$

where the beta function, $r \cdot \beta(\ )$, can be approximated by the relationship (Christiansen et al., 1966):

$$r \cdot \beta(B+1, r) = \left[\frac{b - br + 2}{(d_i + 2)(r+1)} \right] \ldots\ldots \quad (43)$$

To evaluate the coefficients A and B in Equations 34 and 42, a mass balance in the furrow can be written. In this case, assume the total time of application is such that the water just reaches the end of the furrow (ℓ=L, the furrow length). The mass balance is maintained by equating the furrow inflow and the volume remaining in surface storage to the volume infiltrating the soil:

$$V_i = (V_q - V_s)/w \quad \ldots\ldots \quad (44)$$

where,

V_i = volume infiltrating the soil at some time, m^3/m;

V_q = volume introduced into the furrow, m^3;

V_s = storage in the furrow, m^3; and

w = furrow spacing, in meters.

Generally, the furrow inflow, V_q, is measured with small flumes or weirs leaving two unknowns in Equation 44. Wilke and Smerdon (1965) proposed that the average cross-sectional area of the flow could be described by an exponential function of normal depth, d_o:

$$\bar{A}_f = M\, d_o^N \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (45)$$

in which,

$\bar{A}_f$ = average cross-sectional area of the flow, cm^2;

d_o = normal depth, in meters;

M = 8.59; and

N = 1.67.

The expression of flow area as a function of normal depth assumes that the shape of the furrow is known and that the relative shape of the flow profile remains the same along the entire furrow length. Given the variability in surface irrigation, the values of M and N should be determined for each test. The normal depth can be determined by the Manning equation. Wilke and Smerdon (1965) used a roughness coefficient of n=0.047, thereby arriving at d_o as:

$$d_o = 0.60\,(Q/\sqrt{S_o})^{0.4} \quad \ldots\ldots\ldots\ldots\ldots \quad (46)$$

where,

Q = flow rate, l/min; and

S_o = field slope in percent.

If Equation 42 is utilized to describe V_i and Equations 35 and 45 to represent V_s, then Equation 44 can be written:

$$10^{-2} \cdot A \cdot p \cdot t_i^{B+r}\ \beta(B+1, r+1) = \frac{V_q - x_i \cdot \bar{A}_f \cdot 10^{-4}}{w} \quad \ldots \quad (47a)$$

in which,

t_i = time at which mass balance is made; and

x_i = distance the flow advances in t_i minutes, in meters.

Solving for time,

$$A \cdot t_i^{B+r} = \frac{V_q - x_i\ \bar{A}_f \cdot 10^{-4}}{10^{-2} \cdot w \cdot p \cdot \beta(B+1, r+1)} \quad \ldots\ldots\ldots\ldots \quad (47b)$$

When Equation 47b is evaluated for various values of advance time, $0 \le t_i \le t_\ell$, a log-log plot of the results gives a single function of time having a slope of B+r. By knowing r from either equations 36 or 37, and recalling that B=b+1, the infiltration exponent b can be determined. Likewise, A is the ordinate intercept at an abscissa value of 1.0.

The preceding analysis has at least two important advantages for field scale evaluations. First, the approach determines an average furrow infiltration rate expression rather than the point measurements derived from other techniques. Thus, the problem of spatial variability at least along the furrow is appropriately addressed and the variability across the field can be determined by investigating a number of furrows. And secondly, the data necessary to calculate infiltration are easily determined. The investigator diverts a known and constant discharge into the furrow, notes the times until the flow has advanced one-half the field length and the field length, and measures the cross-sectional area. These data along with the field slope and length allow evaluation of the soil intake characteristics.

As with any field evaluation technique, however, this method has a number of weaknesses. The volume of actual field data for verification of the approach is inadequate and the sensitivity of the predictions to the various assumptions has not been determined. Consequently, the estimation of surface storage must be studied further. Specifically, the estimation of average cross-sectional area and the flow depths along the furrow require on-site measurement if possible until the experimental data base becomes large enough to generate verified relationships. It should also be noted that the values of a and b in Equation 33 depend on the discharge introduced into the furrow since the normal depth will be greater. A similar effect will occur as a result of furrow length. The longer the furrow, the less Equation 34 will apply. One aspect of infiltration seldom addressed, but of major importance, is the general decrease in intake rates through an irrigation season due to the effects of previous irrigations and tillage practices. The frequency of irrigations is also an important variable because of the moisture content-hydraulic conductivity function of which Equation 33 is in a sense an approximation.

Predicting Application and Field Efficiencies

A fairly intensive effort has been devoted in recent years to accurately predicting the soil moisture depletion in irrigated fields. The experimental and commercial data currently available suggests that both the timing and the necessary amounts of water to apply can be reasonably well estimated. Accomplishing the scheduling recommendations, however, is another matter in furrow irrigated areas. If the infiltration characteristics have been evaluated over the range of commonly encountered conditions, and the field topographic and operational characteristics are known, the efficiency of irrigations under alternative regimes can be predicted.

This analysis begins with the definition of the depth of moisture needed to refill the crop root zone, D, in cm. Then from Equation 34, the time necessary to infiltrate the desired depth is:

$$t_D = (D/A)^{1/B} \quad \text{. . . . .} \quad (48)$$

where t_D is time in minutes water must infiltrate at a specific point to replace the depth D in the root zone. Because the intake opportunity time varies between the beginning and end of a furrow, the actual infiltrated depths also vary. Three cases for the furrow irrigation regime may be detailed: (a) the under-irrigated case where some of the lower reaches are not completely refilled (Figure 26a); (b) the case where the minimum irrigated area is just refilled (Figure 26b); and (c) the general over-irrigated case (Figure 26c).

The earlier discussion regarding the infiltration evaluation covered only the part of the irrigation encompassed by the advance phase, i.e., the period until the furrow stream reaches the end of the field. Actually, the analysis is valid for periods longer than the time required to advance the field length by assuming that the furrow extends indefinitely. Thus, if the total time water is applied to the furrow (set time) is again represented by t_ℓ, ($t_\ell > t_L$) the length of advance predicted by Equation 35 would be:

$$\ell = p t_\ell^r \quad \text{. . . . .} \quad (49)$$

where ℓ is the total "equivalent" field length, in meters. The volume of infiltration over the length ℓ, V_ℓ, is determined from Equation 42.

Referring to Figures 26a, 26b, and 26c again, it is seen that in order to compute the volume of deep percolation and tailwater, Equation 41b must actually be solved for various fractions of t_ℓ. For example, for any time t' such that $0 < t' < t_\ell$, the resulting equation is:

$$V' = 10^{-2} \cdot A \cdot p \cdot r \cdot t_\ell^{B+r} \int_0^R (1-t)^B \, t^{r-1} \, dt \quad \text{. . . . . . .} \quad (50)$$

where,

V' = the volume of water infiltrated over a segment of the "equivalent" furrow, m^3/m; and

$R = t'/t_\ell$.

Since Equation 50 does not have an exact solution, a numerical integration technique was utilized to compute the integral part of a wide range of values for B, R, and r. A multiple correlation analysis found that the solutions could be related to values of R and B as follows:

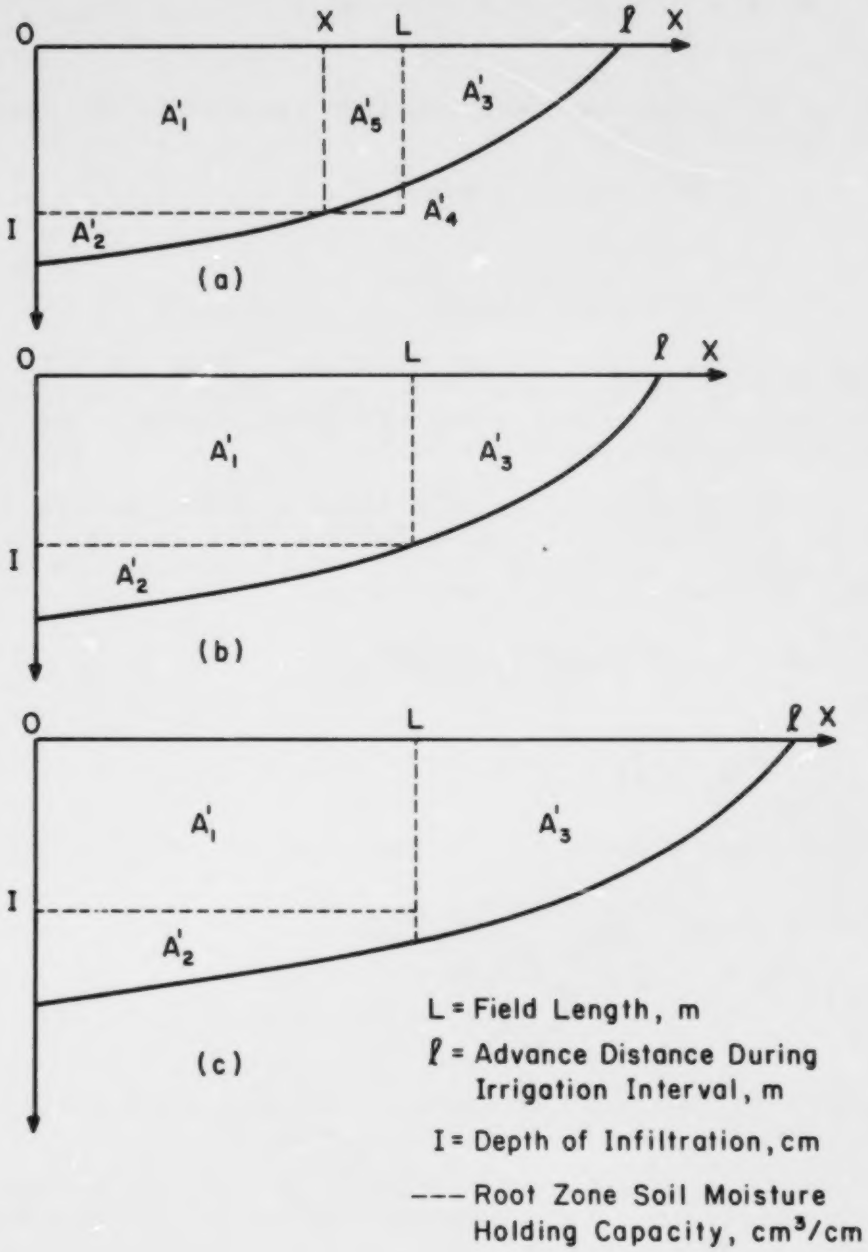

O
X
L
ℓ
X
A'1
A'5
A'3
A'4
I
A'2
(a)
O
L
ℓ
X
A'1
A'3
I
A'2
(b)
O
L
ℓ
X
A'1
A'3
I
A'2
(c)
L = Field Length, m
ℓ = Advance Distance During Irrigation Interval, m
I = Depth of Infiltration, cm
--- Root Zone Soil Moisture Holding Capacity, cm³/cm

Figure 26. Definition sketch of surface irrigation application uniformity for a) the case where part of the field is underirrigated, b) the case of zero underirrigation, and c) conditions of significant overirrigation.

$$M' = r \int_0^R (1-t)^B \, t^{r-1} \, dt = eR^r \quad \ldots\ldots\ldots\ldots \quad (51)$$

where M' is an incomplete beta function related to the upper limit of integration R.

$$e = 0.9598 \exp(-0.3383B) \quad \ldots\ldots\ldots\ldots \quad (52)$$

and,

$$f = 1.0170 \exp(-0.9763B) \quad \ldots\ldots\ldots\ldots \quad (53)$$

The maximum error, ($e_{M'}$), between Equation 51 and the 800 increment numerical solution was $-1.7\,\% \leq e_{M'} \leq 2.7\,\%$. It should also be noted that the parameter r was eliminated by assuming that the relationship in Equation 36 was valid.

It is now possible to utilize the preceding analysis to compute the irrigation efficiency for a furrow system. To do this, two specific subsets of irrigation efficiency are defined. The first, application efficiency, AE, is:

$$AE = \frac{\text{root zone storage}}{\text{total infiltrated volume}}$$

$$= \frac{A'_1 + A'_5}{A'_1 + A'_5 + A'_2} \times 100 \quad \ldots\ldots\ldots\ldots \quad (54)$$

The second, field efficiency, FE, is:

$$FE = \frac{\text{root zone storage}}{\text{total field deliveries}}$$

$$= \frac{A'_1 + A'_5}{A'_1 + A'_2 + A'_3 + A'_5} \times 100 \quad \ldots\ldots\ldots\ldots \quad (55)$$

Note that where the least irrigated areas along the furrow are just refilled, A'_4 and A'_5 are equal to zero.

Values for the respective segments of the infiltrated and runoff volumes along a furrow are determined using the solutions to Equation 50 as follows:

$$A'_1 = X_D \cdot D, \quad X_D \leq L \quad \ldots\ldots\ldots\ldots \quad (56)$$

$$A'_2 = 10^{-2} \cdot A \cdot p \cdot t_\ell^{B+r} \cdot M'_{R_D} - A'_1 \quad \ldots\ldots\ldots\ldots \quad (57)$$

$$A'_5 = 10^{-2}\cdot A\cdot p\cdot t^{B+r}\cdot M'_{R_L} - A'_1 - A'_2, \quad X_D \leq L \quad \ldots\ldots \quad (58)$$

$$A'_5 = 0, \quad X_D \geq L \quad \ldots\ldots \quad (59)$$

$$A'_4 = L\cdot D - A'_1 - A'_5, \quad X_D < L \quad \ldots\ldots \quad (60)$$

$$A'_4 = 0, \quad X_D \geq L \quad \ldots\ldots \quad (61)$$

$$A'_3 = 10^{-2}\cdot A\cdot P\cdot t^{B+r}\left[\frac{b-br+2}{(b+2)(r+1)}\right] - A'_1 - A'_2 - A'_5 \quad \ldots \quad (62)$$

where,

$$M'_{R_D} = r\int_0^{R_D} (1-t)^B\, t^{r-1}\, dt, \qquad R_D = t_D/t_\ell \quad \ldots\ldots \quad (63)$$

and

$$M'_{R_L} = r\int_0^{R_L} (1-t)^B\, t^{r-1}\, dt, \qquad R_L = t_L/t_\ell \quad \ldots\ldots \quad (64)$$

Equations 56-64 can be utilized to develop some general efficiency curves as shown in Figures 27 and 28 (Gerards, 1978).

EVALUATION OF FURROW IRRIGATION IN GRAND VALLEY

The data collection program discussed by Evans et al. (1978) resulted in an average first-of-season cumulative intake function (Equation 34) of:

$$I = 7.82t^{0.40} \quad \ldots\ldots \quad (65)$$

when t is in units of hours rather than minutes. Data collected during the 1977 irrigation season by Gerards (1978) have resulted in a slightly lower value of the exponent B (0.33), but the average value as determined in equation 65 falls within the range characterized in the Valley. The existing value of A (7.82 cm/hr) is thought to be fairly representative. Evans et al. (1978) listed two equations describing the general decline in 24 hour cumulative intake:

$$I_r = 0.999 - 0.2245\cdot N + 0.02089\cdot N^2 \quad \ldots\ldots \quad (66)$$

and

$$I_r = 0.3067 + 0.7032/N^2 \quad \ldots\ldots \quad (67)$$

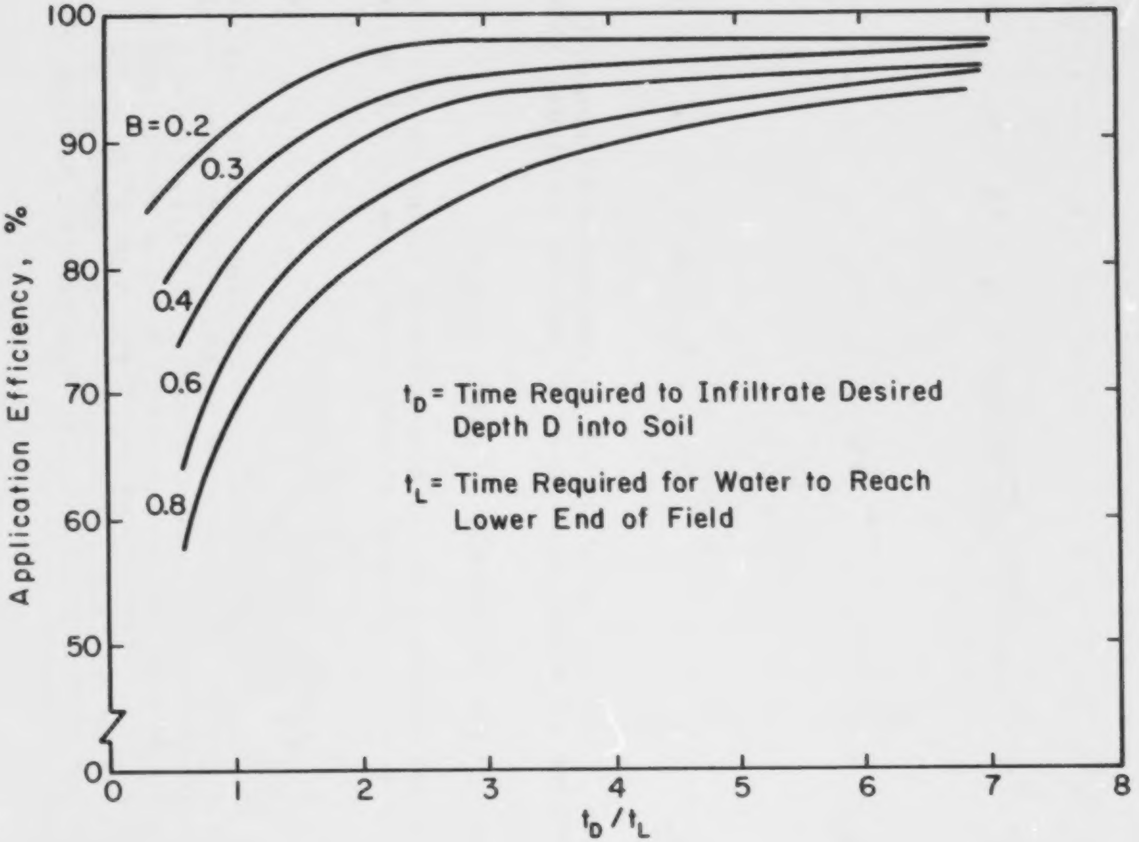


Figure 27. Application efficiency relationship for furrow irrigation for the case of zero underirrigation (after Gerards, 1978).

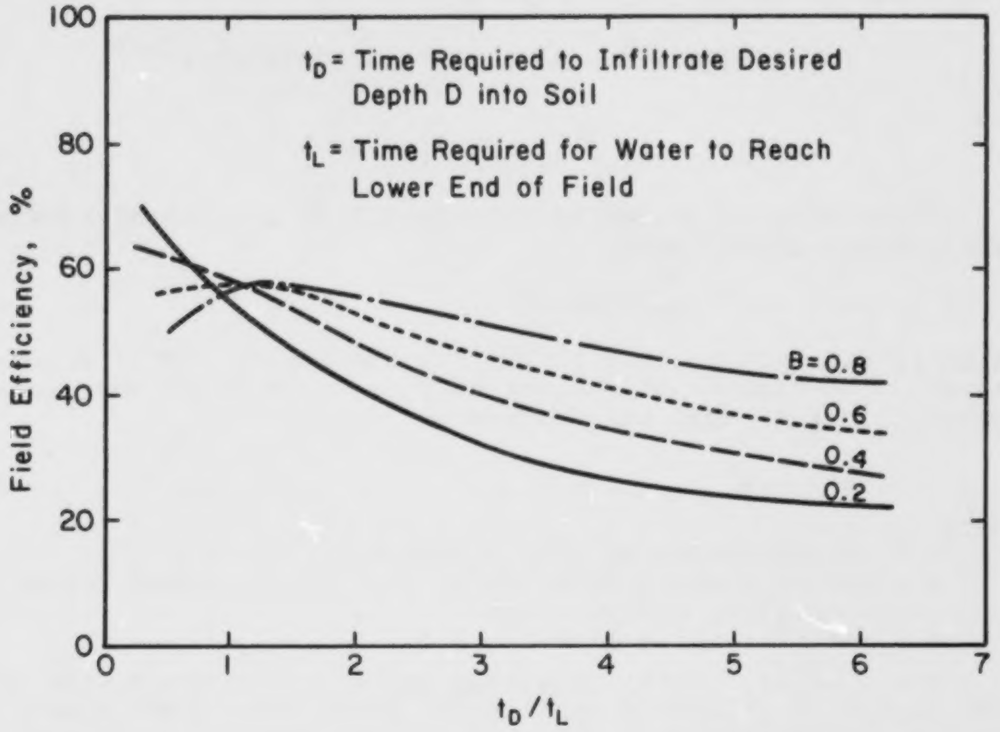


Figure 28. Field efficiency relationships for furrow irrigation for the case of zero underirrigation (after Gerards, 1978).

where,

I_r = relative 24 hour cumulative infiltration; and

N = number of previous irrigations plus 1.0.

Equation 66 was given as an approximation for perennial cropped fields, whereas Equation 67 was for annual crops. Gerards (1978) concluded that the decline in infiltration rate could almost totally be lumped in the A coefficient of Equation 34. Thus, rewriting Equations 65, 66, and 67:

$$I = 7.82(0.999 - 0.2245 \cdot N + 0.02089 \cdot N^2)t^{0.40} \quad . . . (68)$$

and,

$$I = 7.82(0.307 + 0.703/N^2)t^{0.40} \quad . . . . (69)$$

Field data collected by Gerards (1978) on both advance and infiltration showed that,

$$r = 0.977 \exp[-0.63B] \quad . . . . (70)$$

which is reasonably close to the Fok and Bishop (1965) approximation. The results of evaluating p in Equation 35 were less specific, but yielded the expression:

$$p = u \cdot q^s \quad . . . . (71)$$

where,

Q = furrow inflow in liters/minute;

u = factor ranging from 0.1 to 0.2 for the Grand Valley conditions studied; and

s = factor ranging close to 1.0.

Evans et al. (1978) presented three curves describing the time dependent values of application efficiency under typical Grand Valley conditions. These functions assumed uniform water distributions and, therefore, overestimate actual efficiencies 5-10 percent. Using the relationships reported in previous paragraphs, the writers recomputed application and field efficiencies taking uniformity into account. These results are shown in Figure 29 as the dashed lines (the solid lines are the original functions presented by Evans et al., 1978). A summary of the calculations are given in Table 6.

ALTERNATIVES FOR IMPROVING FURROW IRRIGATION

The annual average application efficiency in the Grand Valley according to Walker et al. (1977) is approximately 64 percent. Table 6 indicates that if the irrigations were managed so that the minimally irrigated areas at the bottom end of a field were not overirrigated, the resulting average application

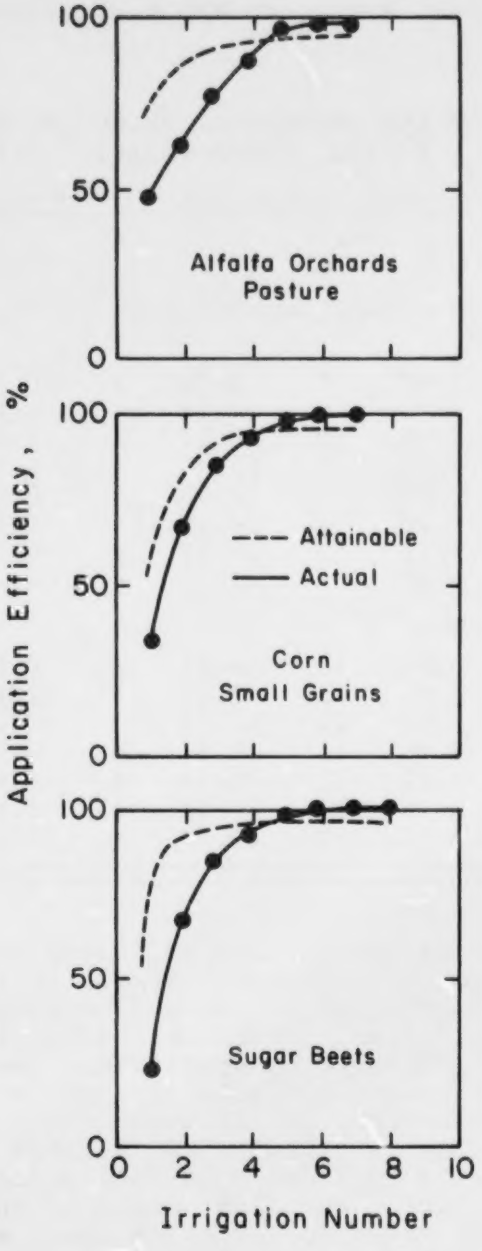


Figure 29. Seasonal distribution of computed application efficiencies for common crops grown in the Grand Valley.

efficiencies would approach 85 to 90 percent. Field efficiencies will continue to be low, averaging about 36 percent under the well-managed cases.

TABLE 6. FIELD EFFICIENCY CALCULATIONS FOR A TYPICAL GRAND VALLEY FIELD

Irrigation No.	A	D (cm)	t_D (hr)	t_L (hr)	t_D/t_L	AE	FE
Annual Crops							
1	7.82	9	1.42	8	0.18	50	65
2	3.71	9	9.12	4	2.29	90	47
3	2.95	9	16.26	4	4.07	92	40
4	2.69	9	20.48	4	5.12	93	33
5	2.57	9	22.95	4	5.14	94	30
6	2.50	9	24.59	4	6.15	95	30
7	2.50	9	24.59	4	6.15	95	30
8	2.50	9	24.59	4	6.15	95	30
Perennial Crops							
1	6.22	11	4.16	6	0.69	73	55
2	4.95	11	7.36	4	1.84	87	50
3	4.02	11	12.39	4	3.10	91	44
4	3.40	11	18.83	4	4.71	93	33
5	3.12	11	23.34	4	5.84	94	30
6	3.12	11	23.34	4	5.84	94	30
7	3.12	11	23.34	4	5.84	94	30

In order to improve application efficiencies in the Grand Valley, two steps require attention. First, irrigation scheduling should be based on updating the soil moisture conditions in the lower ends of the fields. These data would indicate the minimum depth of irrigation to be applied and the total time water should remain in the field after it has reached the end of the furrows. This procedure, if followed, would achieve the 85 to 90 percent efficiency described as attainable above. The second step in improving application efficiencies involves more frequent irrigations during the first month of the irrigation season. More frequent water applications imply much lower (and linear) infiltration rates, thereby maximizing the uniformity of the irrigation and minimizing the differences between the upper and lower ends of the fields. In looking at Table 6 and comparing t_D and t_L, the added labor by the irrigator can be determined. As an example, consider the annually cropped field irrigated consistently in 4-24 hour sets. To reach the 85-90 percent application efficiency, the set times need to be t_D+t_L.

Thus, during the first irrigation, the field should be irrigated in 40 hours rather than the usual 96 hours (an increase in labor of 96/40 = 2.4 times). Over the entire season, the additional labor requirements for annually cropped and perennially cropped fields average 141 percent and 149 percent of existing irrigation labor requirements, respectively. Converting to a high frequency irrigation regime during the first month of the irrigation season would increase labor requirements by almost an order of magnitude and it is doubtful if this much time would be available. Consequently, the high frequency case would require a restructured irrigation system, similar to the cut-back method discussed in the following paragraph.

Even though furrow irrigation application efficiencies can be substantially improved by increasing the labor input to existing irrigation practices, there is very little, if any, real benefit to the irrigator if he does so. In fact, the overirrigation now occurring creates very few detriments to the farm production system in the Grand Valley. If minimal field tailwater is to be achieved through increased field or farm efficiency, additional labor to improve these efficiencies would be even less feasible. Consequently, in the Grand Valley, it is doubtful that anything short of legislative mandate would induce the necessary labor inputs to control the salinity contributions from on-farm sources; the reductions need to be achieved with structural measures. One such measure is automated cut-back irrigation as described by Evans (1977). With less labor than that being invested currently, the irrigator can achieve the 85-90 percent application efficiency and at the same time almost eliminate field tailwater. High frequency irrigations are possible with small amounts of additional labor.

SECTION 9

BORDER IRRIGATION

DESCRIPTION OF BORDER IRRIGATION

One of the oldest and most widely practiced method of irrigation in the world is border irrigation. Border irrigation uses earthen dikes or "borders" to contain the water within specified boundaries. These borders can be constructed on a sloping or graded surface or to form basins or level borders. Borders may also be constructed following the contour in hilly areas and may be either sloping or level (terraces).

On very steep areas where land leveling costs would be prohibitive and the soils are usually not deep enough for leveling, a variation of flood irrigation using dikes is used. This method is often called guide border irrigation and is used on pasture or hay crops. Generally speaking, these "borders" are spaced fairly close together, the runs are short, and uniformities and efficiencies are low. This method has little application in the Grand Valley, but is used in high mountain meadows and grasslands.

The border method is suitable for a wide range of soil textures. However, extensive and exact land leveling and shaping is usually required for efficient water use and uniform distribution. In addition, border dimensions can usually be designed for efficient operation of planting, tillage, and harvesting equipment.

Border irrigation efficiencies can be greatly increased by automation and the method, in general, is especially amenable to automation. Howe and Heerman (1970) presented a strong case for the automation of border irrigation. In graded borders, the uniformity and efficiency depend on the precise cut-off time of irrigation, which is often not practical from a labor viewpoint. In level borders or basins, the exact amount of water applied is critical since too much could cause overtopping of the dikes and/or excessive deep percolation losses. Humphreys (1971), Sweeten and Garton (1970), Erie and Dedrick (1976), Evans (1977), and others have described several relatively inexpensive methods by which these systems can be automated.

The Water Resources Council (1971) estimated the attainable field efficiency (without automation) in the Upper Colorado River Basin to range from 60 to 75 percent for strip or graded borders and 50 to 80 percent for level borders or basins.

Conversations with local irrigators and canal company officials in the Grand Valley have shown that there is a definite opposition to any type of border irrigation due to crusting (and thereby germination) problems with this method. However, there are other areas in the western United States and the world which use this method on similar soils where crusting is controlled by several different management techniques.

Graded Border Irrigation

Graded border irrigation requires that the field be divided into strips varying from 10 to 20 meters or more in width and extending 100 to 800 meters in length. The slope of these "bordered strips" should not exceed 2 percent for row crops, which would apply to most of the best lands in the Grand Valley. Slopes can be as high as 6 percent for small grains and pastures or hay.

Field efficiency of graded borders is usually about 65 percent, and the application efficiency ranges from 70 to 80 percent with proper management. Bos and Nugteren (1974) in a worldwide survey of irrigation efficiencies reported that the average application efficiency for graded borders was about 53 percent. The average for the United States was 57 percent. A limitation of graded border irrigation is that it generally requires considerable skill and a higher degree of management than does furrow irrigation. However, labor requirements can be lower than other methods.

Graded borders are suitable for all close growing crops (except rice or other crops grown in ponded water) such as small grains, alfalfa, and grass hay as well as orchards and vineyards. It is best suited for soils with moderately low to moderately high infiltration rates which compares with the range of the Grand Valley soils. This method should not be used on coarse, sandy soils with high intake rates or on soils with very low intake rates (where basins should be used) since the opportunity time for adequate infiltration would be quite long and both deep percolation and runoff would be excessive.

Border strips must be leveled carefully and all cross slope eliminated. At the present time, land leveling in the Grand Valley would cost approximately \$370/hectare (\$150/acre) to convert to graded border irrigation.

Ideally, the correct management of graded borders requires that the proper amount of water be turned into the border, and the stream be turned off before the water reaches the end of the border. The purpose is to apply a sheet of water evenly over the border for uniform infiltration and minimal tailwater. As a rule-of-thumb, the recession time is usually about 25 percent of the required opportunity time.

Jensen and Howe (1965) studied low-gradient borders in the sandy loam soils near Scottsbluff, Nebraska, and found that application efficiencies (water stored in root zone divided by delivered water) of 90 to 95 percent were easily obtained. For maximum efficiency they found that the rate of water application should be from three to five times the average intake rate. In addition, if the net depth of application is greater than or equal to 5 percent of the total fall in the border, an "end-block" to impound the water is recommended to increase efficiency.

Level Border Irrigation

The level border or basin irrigation method consists of turning relatively large streams of water into level plots surrounded by dikes or levees to form basins. There is no runoff. This method is especially adaptable to soils with moderate to low permeability rates where other irrigation methods do not provide an adequate infiltration opportunity time. At this time, the USDA, Agricultural Research Service is evaluating a modification of this type of irrigation in the Grand Valley. They are using a concept of level borders with furrows in an attempt to circumvent crusting and resulting germination problems experienced in earlier graded border irrigation experiments in the area.

To avoid excessive deep percolation, the design application efficiency should not be less than 80 percent. With proper management, efficiencies of 90 percent or more are not uncommon.

It is often very difficult to construct these level basins, and it is also very difficult to maintain a perfectly level land surface. The advent of laser controlled land planes and scrapers has greatly helped this problem. However, to avoid low areas or reverse grades, which would reduce the application efficiency, the basins are often leveled with a slight grade in the direction of irrigation. Land leveling and shaping costs for level borders in the Grand Valley are presently estimated to be about $620/hectare ($250/acre).

In the study cited earlier by Bos and Nugteren (1974), application efficiency on a worldwide basis for level borders or basins averaged about 58 percent. In the United States the average value was 59 percent. These average figures are lowered considerably by rice irrigation which is a continuous ponding method, does not account for precipitation, and generally has high deep percolation losses.

HYDRAULICS OF BORDER IRRIGATION

The basic hydraulics of surface irrigation were described in Section 8, where recession was assumed to be negligible for the furrow irrigated soils and field slopes of the Grand Valley. However, this assumption cannot be made for border irrigation where recession is a very important component of the irrigation process.

Evans et al. (1970), Kincaid et al. (1972), Kincaid (1970), Lewis and Milne (1938), Hall (1956), Bassett (1973), Wu (1972), Phillips and Farrell (1969), and others have presented several methods for the calculation of border hydraulics. Recent work by Katopodes and Strelkoff (1977), Strelkoff and Katopodes (1977), and Strelkoff (1977) has developed a more complete model for hydraulic flow which will closely predict recession. For the field slopes found in the Grand Valley (about 70 percent of the fields between 0.5 and 2 percent slopes), it is sufficient to use the algebraic approaches proposed by Strelkoff (1977). The more rigorous zero inertia model would be more applicable if the slopes were relatively small (roughly about 0.2 percent or less).

Strelkoff (1977) proposed the use of an algebraic model for the calculation of border hydraulics based on the assumption that the downstream depth is constant and normal for the unit runoff at the end of the depletion phase, which is the start of the recession phase.

The advance curve can be approximated by the volume balance approach of Hart et al. (1968)

$$X = \frac{qt}{r_y y_o + r_I I_o} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (72)$$

where X is the advance distance,
q is the volume inflow per unit width of border
t is equal to time
r_y is a shape factor, approximately equal to 0.8
y_o is the normal depth for q
I_o is the depth of infiltration at the head of the border given by the Kostiakov equation as defined in Section 8.

$$I_o = At^B \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (73)$$

and the subsurface shape factor r_I is equal

$$r_I = \frac{1}{1+B} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (74)$$

Recession can be calculated by the following differential equation:

$$\frac{d}{dt}\left(\frac{\ell^2 S_y}{2}\right) = \overline{I}\ell - \frac{C_u}{n} S_o^{1/2} (S_y \ell)^{5/3} \quad . . . . (75)$$

where ℓ = length of the field which is inundated by the receding water front

S_y = slope of the water surface

S_o = slope of the ground surface

$\overline{I}$ = average infiltration rate

C_u = coefficient for units in the Manning equation (in the cgs systems, $C_u = 1$)

n = coefficient of roughness for the Mannings equation.

The second term in the right-hand side of the equation represents the runoff rate out the downstream end of the border where the flow is assumed to be at normal depth. The above equation can be simplified by the division of the formula by $S_y \ell$ and defining a new constant:

$$C = \frac{C_u S_o^{1/2} S_y^{5/2}}{n\overline{I}} \quad . . . . (76)$$

For most soils $\overline{I}$ will approach a constant value with large infiltration times, which is usually the case for recession. Using these assumptions, Equation 75 reduces to the form of:

$$-\frac{S_y}{\overline{I}} \int_L^{\ell} \frac{d\ell}{1+c\ell^{2/3}} = \int_{t_r}^{t} d_t \quad . . . . (77)$$

where L is the total length of the field, and t_r is the time at which the recession phase commences.

The volume of runoff at time t_r (for the depletion phase) before starting the recession phase is given as:

$$V_{ro}(t_r) = V_o - V_y(t_r) - V_I(t_r) \quad . . . . (78)$$

where

$$V_o = q_o t_{co} \quad . . . . (79)$$

$$V_t(t_r) = \frac{S_y L^2}{2} \quad \ldots \ldots \quad (80)$$

$$V_I(t_r) = \frac{I(t_r) + J(t_r - t_L)}{2} \cdot L \quad \ldots \ldots \quad (81)$$

and t_{co} is the time at which inflow into the border is stopped and t_L is the advance time for water to reach the end of the border. The computation of runoff during the recession phase is expressed as a differential equation:

$$\frac{dV_{ro}}{dt} = \frac{C_u}{n} \cdot S_o^{1/2} \, S_y^{5/3} \, \ell^{5/3} = q_o - q_{inf} \quad \ldots \quad (82)$$

where q_{inf} = volume infiltrated.

By use of the above equations it is a relatively simple matter to compute the depth of infiltration at any point along the field and the total runoff for any q_o. At that point, by use of the techniques described in Section 8, the application efficiencies for border irrigation in the Grand Valley can be easily computed.

EVALUATION OF BORDER IRRIGATION IN THE GRAND VALLEY

As mentioned previously, no attempt was made as part of this project to physically evaluate graded border irrigations. Therefore, this analysis will be based on data collected in the Grand Valley by other investigators such as Gilley (1968), Howe and Heerman (1970), Kincaid (1970), and Evans et al. (1970).

Graded Borders

Gilley (1968) and Howe and Heerman (1970) used a uniformity coefficient for graded border irrigation as defined by Christiansen (1942):

$$UCC = 100\left(1 - \frac{y}{d}\right) \quad \ldots \ldots \quad (83)$$

where y = average of the absolute deviations of the measurements
d = average measurement.

These uniformity coefficients were calculated for measurements of intake opportunity time (UCC_t) and soil moisture (UCC_w). The results indicated that approximately 30 percent of all irrigations had a UCC_w of at least 90 percent and 85 percent of all irrigations had a UCC_w of at least 80 percent. The seasonal average UCC_w for the Grand Valley soils (Billings silty clay loam) was quite close to 90 percent.

The stream size required to attain uniform intake opportunity time for one site in Grand Valley decreased from 0.01 m^3/sec to 0.006 m^3/sec per meter of border width (0.11 cfs to 0.06 cfs per foot of border width) as the season progressed. The intake opportunity time doubled from 60 minutes to 120 minutes while the infiltrated depth decreased from 10 to 7.6 cm (4 to 3 inches), and the recession rates decreased from 3.05 to 1.52 meters per minute (10 to 5 feet per minute). These results are quite consistent with results found elsewhere in the Valley for furrow irrigation.

Howe and Heerman (1970) presented envelope curves (Figure 30) for infiltration depth versus time. Approximately 75 percent of these data fit within these curves. The upper curve corresponds to a 1.0 intake family as defined by the USDA-SCS, and the lower curve is a 0.5 intake family.

There was no application efficiency information reported for the studies, and personal communication with the investigators has indicated that efficiency data from this work would not be suitable for analysis. Therefore, utilizing the published data collected in graded borders in the Grand Valley by Gilley (1968), Howe and Heerman (1970), and Kincaid (1970), an analysis was performed using the Strelkoff (1977) algebraic method.

For the purposes of illustration, the results of this analysis for the "average" field in the Grand Valley (slope = 1.25 percent, length = 150 meters) are shown in Figure 31. The analysis was done using selected application rates per unit width and at cut-off times of 80, 100, 120, 150, and 200 percent of the time for the advancing water front to reach the end of the field. The time required for the flow to advance the full length of the border is shown on each line of the graphs in Figure 31.

Extending this analysis indicated that row crops such as corn would be expected to have a seasonal application efficiency of about 80 percent. Utilizing a similar distribution of the infiltrated depths as presented in Figure 20 of Section 5, alfalfa would seasonally contribute about 5 metric tons of salt per hectare and corn about 12 metric tons per hectare. The differences in potential salt loading between graded borders and existing furrow irrigation practices with good management appear to be insignificant. The cost-effectiveness of graded borders would be poorer than furrow irrigation due to the increased costs of land leveling. For both furrows and graded borders, the infiltration characteristics of the soils of the Grand Valley are the controlling factors and not the method of application. Therefore, it can be concluded that graded borders offer little advantage over furrow irrigation, and this change is not warranted.

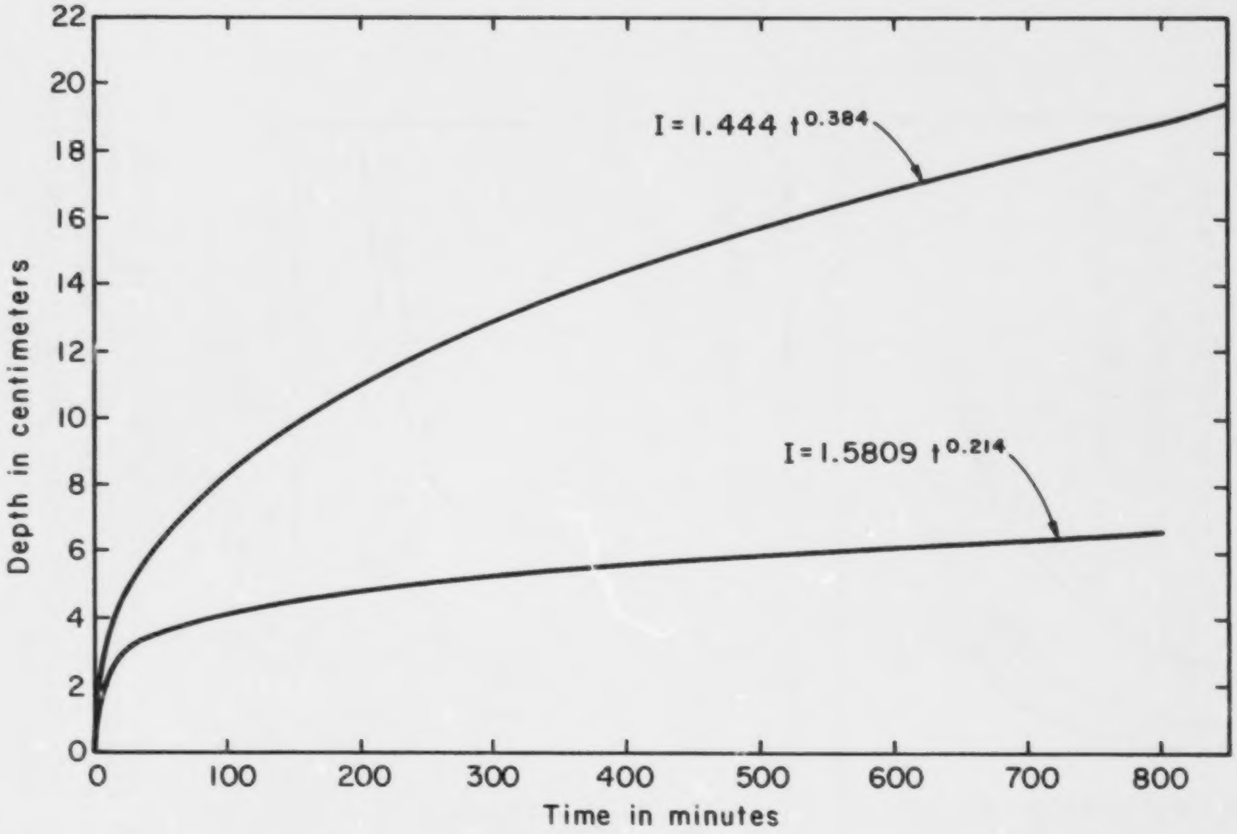


Figure 30. Characteristic intake curves for graded border irrigation in the Grand Valley (Howe and Heerman, 1970).

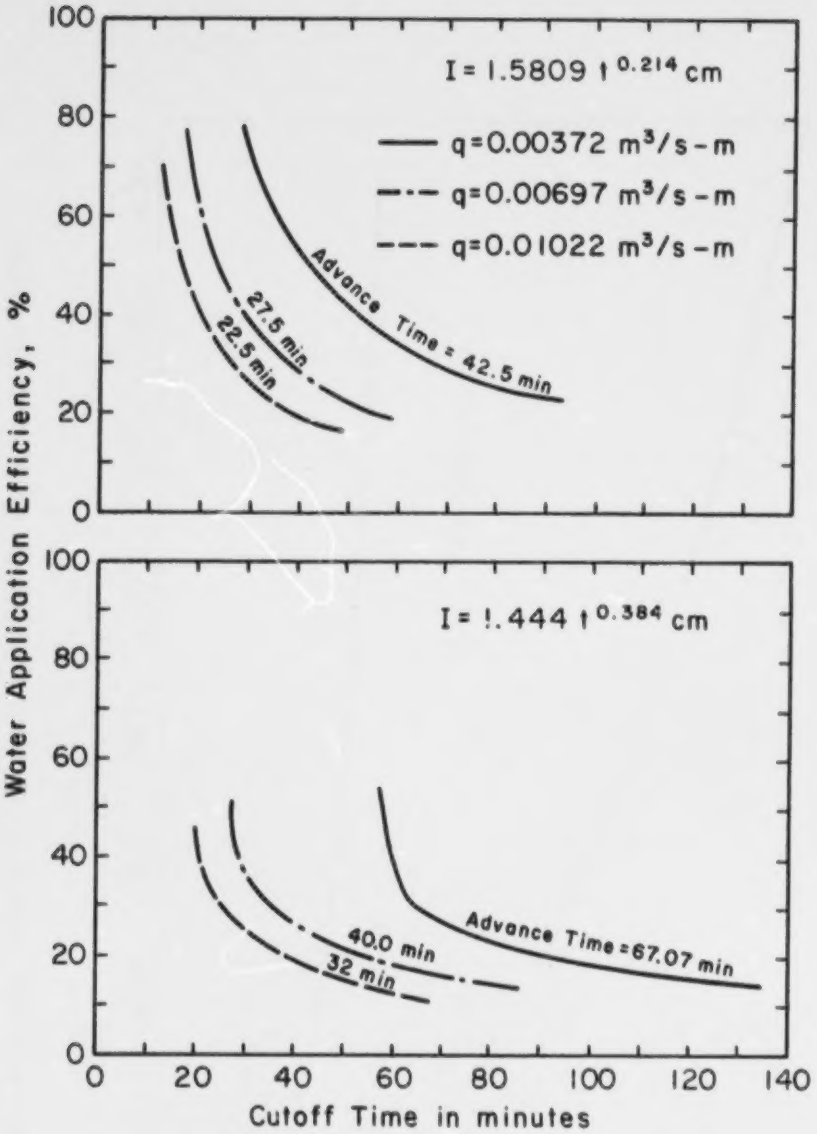


Figure 31. Application efficiency as a function of the calculated cut-off time (t_{co}) for the "average" field of 1.25 percent slope, 150 meter lengths (50 percent soil moisture depletion, discharge per unit width).

Utilizing data from the SCS National Engineering Handbook on border irrigation (1974), a net depth of application on a 1 percent slope with end blocks on graded borders would have a maximum border length of 667 feet (203.3 meters). A 1.5 percent slope would have a maximum length of 444 feet (135.3 meters). As was shown in Section 5, the median field slope (Figure 19) in the Valley is about 1.25 percent and the median field length (Figure 18) is about 160 meters (525 feet) with 75 percent of the fields under 247 meters (810 feet) in length. From these figures it is obvious that a large portion of the Valley could easily and efficiently be converted to graded border irrigation if it was proven advantageous to change.

Level Borders

As was mentioned previously, there is no data on level borders in the Grand Valley, but at the present time the USDA-ARS is conducting experiments in the Grand Valley on level borders with furrows. Use of the furrows is an attempt to prevent crusting problems which were encountered in the earlier investigation of graded borders. This is because the water would not cover the top of the furrows where the crops would be planted.

Assuming that these problems can be solved, the very high application efficiencies possible with level borders provides a very high potential as a salinity control measure. However, they do require a much higher degree of management than presently exists in the area. In addition, since there is no runoff, the potential for conserving water is obvious.

Due to the high uniformity and control afforded by properly designed and constructed level borders with good water management practices, it can be concluded that with a seasonal application efficiency of 90 percent (with a similar seasonal infiltration distribution to the one used previously), the annual potential salt load could be as low as 2.10 metric tons per hectare. With an 80 percent seasonal application efficiency, the annual salt contribution would be about 5.15 metric tons per hectare. Again, due to soil infiltration characteristics, annual row crops such as corn would be expected to have the higher contribution, while established crops such as alfalfa and pasture would have the lower value.

Land leveling costs for level border would be about \$620/hectare (\$250/acre) and a lined delivery system and irrigation scheduling would add approximately an additional \$400/ hectare (\$160/acre) for a total estimated cost of \$1,020/hectare, based on the median field size in the Grand Valley of 2 hectares (5 acres).

At an 80 percent seasonal application efficiency, the cost-effectiveness of a level border system compared to a conservative value of 8 metric ton per hectare contribution under existing practices (8.00-5.15 = 2.85 metric ton/hectare reduction) would be approximately $358 per metric ton of salt removed. This would be without automation, but imposing a very good water management program. At the 90 percent seasonal application efficiency, the cost-effectiveness would be $173 per metric ton of salt removed per hectare (8.0-2.1 = 5.9 ton reduction per hectare). As can be seen from this analysis, the cost-effectiveness is quite sensitive to the type of crops, or more specifically to the soil infiltration characteristics due to cropping practices and patterns. Automation would add little cost to these systems, but would provide significant advantages in maintaining a high degree of water management. Without automation, the labor requirements would be considerable and perhaps not acceptable to local growers.

As discussed earlier, 75 percent of the fields in the Grand Valley are less then 247 meters (810 feet), and by using the criteria presented by the SCS National Engineering Handbook on level borders (Figure 32), it can be seen that a large portion of the Valley could be converted to level borders. It is probable that an application efficiency of 90 percent is the upper limit of which would be expected for the Grand Valley. However, since there are several problems with using this method of irrigation in the area which needs to be addressed by further research, level borders will not be considered as potential cost-effective salinity control measures in this analysis.

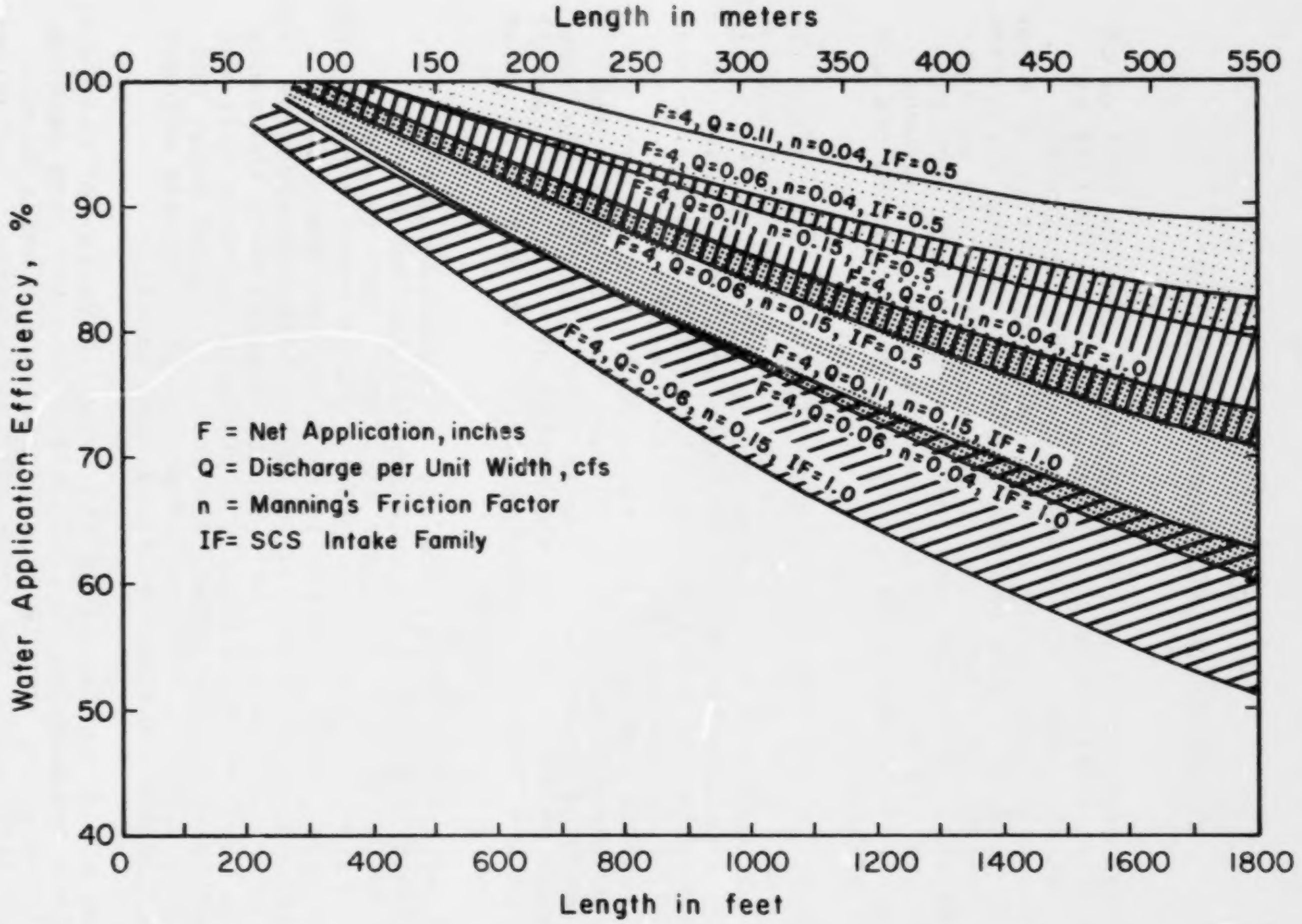


Figure 32. Application efficiency as a function of length for level borders (USDA-SCS, Border Irrigation, 1974). (η = 0.15 for early season irrigations, η = 0.04 for late season irrigations).

SECTION 10

EVALUATION OF SPRINKLER IRRIGATION

Sprinkler irrigation is one alternative for the control of irrigation water application which influences the quality of irrigation return flows. Sprinkler and trickle irrigation systems are a mechanical means by which the application of water can be controlled much more precisely than by surface irrigation methods. Furthermore, these mechanical systems can be automatically or manually operated, and they can apply water continuously or intermittantly in any required quantity. If properly designed, sprinklers should have very little surface runoff and can be very efficient.

Reduction in the amount of return flow will also reduce the total salt loading of the return flows, and for sprinklers this is usually accomplished by reducing the leaching fraction or, in other words, reducing the amount of water applied in relation to the evapotranspiration requirements of the crop. Bernstein and Francois (1973) of the U.S. Salinity Laboratory have found that leaching fractions can be reduced to as much as one-fourth of presently recommended values with no reduction in yields for alfalfa. Leaching fractions as low as 2 or 3 percent (due more to soil characteristics than to the method of water application) are common in the Imperial Valley of California, one of the most productive areas in the world.

Sprinkler irrigation systems are recommended and used on practically all types of soils with few limitations due to topography and on almost all types of crops. This type of irrigation, with its flexibility and efficient water control, has permitted a wider range of soils to be irrigated than have surface water application methods. It has thus allowed more land to be classed as irrigable. As a direct result, many thousands of hectares, which were previously considered suitable only for dryland farming or as wasteland, are being irrigated today and producing high yields. This phenomenon is particularly evident in eastern Colorado, western Nebraska, and Kansas.

On some saline soils, as in the Imperial Valley of California, sprinklers are recommended for better leaching and crop germination. Sprinklers are especially desirable where soils have a high permeability and/or low water holding capacity. Sprinklers can offer distinct advantages over other irrigation methods in dense soils with low permeabilities. In areas where labor costs are high for surface irrigation, sprinklers are the most economical way to apply water. In other areas where water costs are high, sprinklers have proven the most economical method since surface runoff can be minimal. In many cases, sprinklers have been shown to increase yields. In the fresh vegetable and fruit market where color and quality are very important, sprinklers have some advantages over surface irrigation methods.

Sprinklers can have multiple uses. The same equipment can be used for irrigation, crop cooling, frost control, and the application of pesticides, herbicides, and fertilizers. In addition, modern farming practices which require large equipment and large fields for economical farming operations are easily irrigated by sprinklers with no reduction in efficiency.

Many areas in the United States, which annually receive more than enough precipitation to satisfy crop requirements, are installing supplemental irrigation systems. This is due to the fact that rainfall often does not fall at exactly the right time in the right quantities. A timely irrigation at a critical crop growth stage, applying only a few inches of water, can often more than double yields. Sprinklers are used in a large number of these supplemental irrigation systems due to their adaptability to large topographic differences and soil conditions.

Sprinklers, like most physical systems, do have disadvantages. Damage to some crops has been observed when poor quality irrigation water has been applied to the foliage by sprinklers (Harding et al., 1958). Also, poor quality water can leave undesirable deposits or coloring on the leaves or fruit of the crop. Sprinklers are also capable of increasing the incidence of certain crop diseases such as fire blight in pears, fungi or foliar bacteria. A major disadvantage of sprinklers is the relatively high cost, especially for solid-set systems, in comparison to surface irrigation methods. When gravity cannot supply sufficient head to operate the system, sprinklers can require large amounts of energy when the water has to be pumped to supply the necessary pressure. In many cases, it is often more economical to use conventional surface irrigation systems. The advantages and disadvantages of sprinkler systems must be assessed economically with other irrigation methods. Likewise, individual types of sprinkler systems should be compared to one another.

EVALUATING SPRINKLER SYSTEMS

In evaluating any type of irrigation system, there are several variables which all systems have in common and which must be determined for a complete analysis. These include infiltration characteristics of the soil, uniformity of water application, the application efficiency, crop water requirements and the irrigation frequency.

An important advantage of sprinkler irrigation is that the application rate can be designed so that the average infiltration value of the soil is not exceeded, thereby eliminating tailwater runoff. Fitting the system to the soil characteristics is important since runoff is economically undesirable because of the higher cost of water. As described in an earlier section of this report (Section 7), the infiltration rate is a factor of slope and vegetative cover as well as the soil's physical and chemical characteristics. Therefore, each individual sprinkler system is site-specific. Application rates are controlled by the sprinkler head design, nozzle sizes, and the pressure at the nozzle. The wide selection of available sprinkler heads and nozzle sizes usually permits a designer to select the proper combination to meet the specific soil and crop requirements. If the sprinkler is to be used for purposes other than irrigation, such as frost control, these uses also influence sprinkler selection. In short, the application rate is a function of design, including pump selection, sprinkler selection, and pipe sizes.

The uniformity of application of a sprinkler system is a measure of proper design. Generally, the higher the uniformity, the better the design. Experience in the field has indicated that water distribution is usually satisfactory if the uniformity coefficient is greater than 70 percent. For purposes such as frost protection or cooling, it is desirable to maintain a uniformity coefficient greater than 80 percent. The uniformity coefficient is also often called the distribution efficiency.

An individual nonoverlapping sprinkler generally has a nonuniform distribution pattern. However, with the proper design, considering overlapping from other sprinklers, these differences can be reduced.

Sprinkler distribution patterns have been described by several statistical coefficients. The first was proposed by Christiansen (1942) who proposed a uniformity coefficient (UCC) for sprinkler systems:

$$UCC = 1.0 - \sum_{i=1}^{n} \frac{(y_i - \bar{y})}{N \bar{y}} \quad \ldots\ldots\ldots\ldots \quad (84)$$

where y_i is the depth of the ith observation

$\bar{y}$ is the average depth applied

N is the number of equally spaced observations.

A perfectly uniform distribution is 1.0.

There are several other suggested distribution coefficients including Hart (1961) and Hart and Reynolds (1965) who proposed that the precipitation from sprinklers was a normal (Gaussian) distribution and the coefficient (UCH) could be described as:

$$UCH = 1 - \frac{0.798\ s}{\bar{y}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (85)$$

where s is the standard deviation of the depth measurements. Hart (1961) and Seniwengse et al. (1972) established the relationship between UCC and UCH as:

$$UCC = 0.030 + 0.958\ UCH,\ (r^2 = 0.888) \quad \ldots\ldots \quad (86)$$

Karmeli (1977) proposed that a simple and effective statistical description of uniformity was a linear regression. The linear function is described as:

$$Y = a + b\ X \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (87)$$

where Y is a dimensionless precipitation depth of $(y/\bar{y})$
X is the fractional area
a,b are linear regression constants (a is Y_{min}, b is the slope of the line)
$\underline{y}$ is the depth of precipitation
$\bar{y}$ is the mean of the observed depths.

The uniformity coefficient (UCL) is then described as:

$$UCL = 1.0 - 0.25\ b \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (88)$$

This relationship can be seen in Figure 33a. Use of the UCL as a statistical description offers many advantages over the UCC and UCH. For example, the deficiently watered area, the average watered area, the surplus watered area, and the respective volumes of water in each of these areas are easily calculated.

Since the UCL is a description of system performance, Y can also be defined as the depth of water applied (y') divided by the average depth of the water over the field ($\bar{y}'$). The amount of water required is the soil moisture deficit and will equal a fraction of Y=1.0 shown in Figure 33b. Therefore, Figure 33b can also be interpreted as the fractional amount of water required versus the fractional area. Or, in other words, the horizontal required water application line can be shifted up or down to intercept any point on the Y-axis. The maximum practical application from the agronomic standpoint would be at $Y=Y_{min}$ where none of the area would be underirrigated; however, much of the area will be overirrigated. That point will be where 100 percent of the irrigated area will receive at least that dimensionless depth of water. Operation above this point would excessively waste water

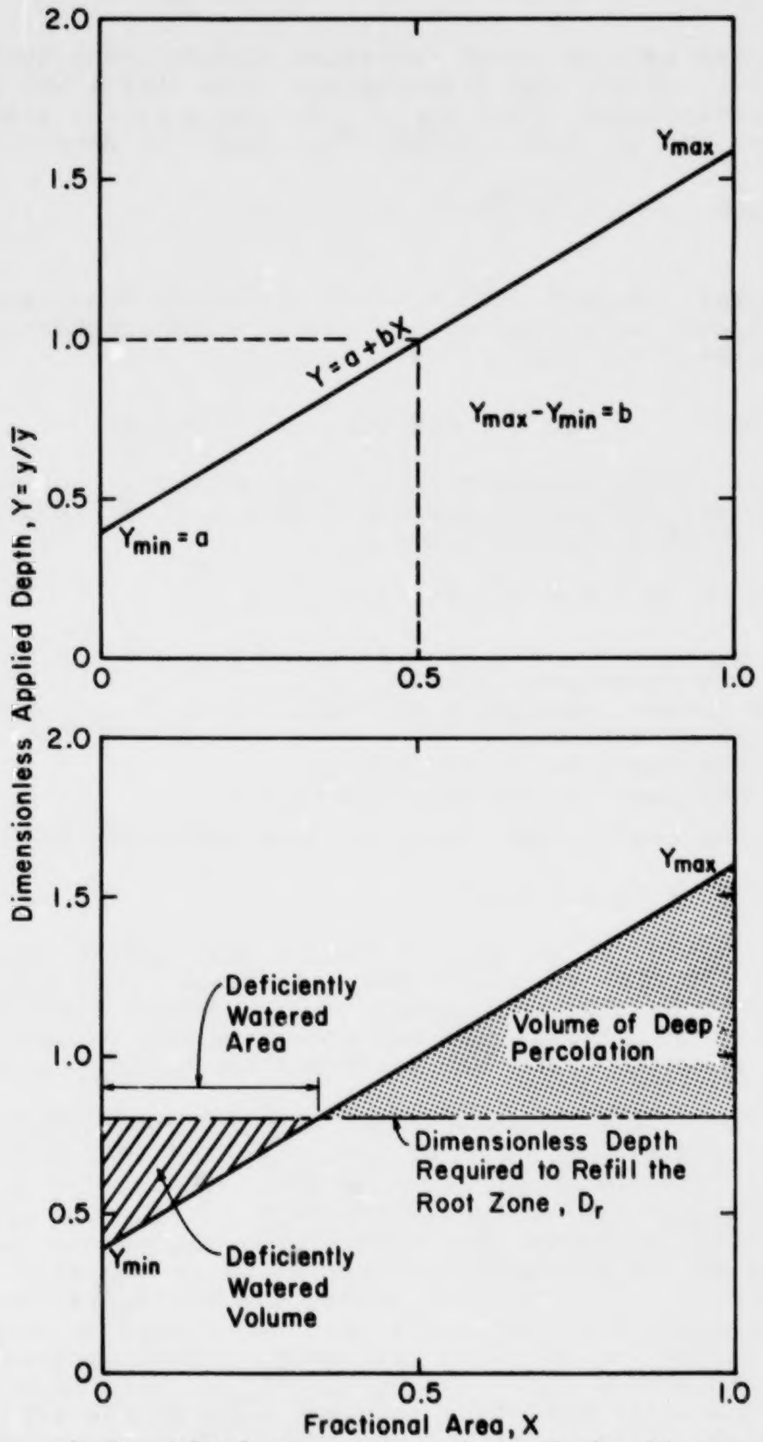


Figure 33. a) Graphical representation of the linear uniformity coefficient; b) the uniformity coefficient as related to system performance.

and energy. Operation of the sprinkler system at the Y-intercept of the requirement line ($Y=D_r=1.0$) would have 50 percent of the area underirrigated and 50 percent overirrigated. Since the average application would equal the average amount required (or $Y=1.0$), this would be an advantageous level to operate the system for a return flow quality program. Obviously, a 50 percent areal deficit would be unacceptable to a grower and a level somewhere between the two levels could be established. This analysis assumes there is no surface runoff.

Utilizing the concept shown in Figure 33b, it is quite easy to compute the application efficiency if a specified amount of the area is deficiently watered:

$$\text{Application Efficiency} = \frac{\text{root zone storage}}{\text{gross application}} \quad . \; . \; . \; (89)$$

$$AE = \frac{D_r - \dfrac{(1-Y_{min})^2}{2b}}{1} \quad = \frac{D_r - \dfrac{(1-Y_{min})^2}{2b}}{1} \quad . \; . \; . \; . \; . \; (89a)$$

$$= D_r - \frac{(1-a)^2}{2b} \quad . \; . \; . \; . \; . \; . \; . \; (89b)$$

The quantity $D_r - (1-a)^2/2b$ is the dimensionless volume of applied water actually stored in the root zone, and the dimensionless volume actually applied is 1.0.

The volume of deep percolation can be obtained by

$$D_p \; = \; (1-AE)D_a \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (90)$$

where D_p is the depth of deep percolation in millimeters
D_a is the average depth of applied irrigation water in millimeters
AE is the application efficiency.

The salinity reduction achieved by a sprinkler conversion depends on the corresponding decrease in the volume of deep percolation attributed to converting previously surface irrigated lands to sprinkler systems. Lands already sprinkler irrigated would probably not convert to surface systems, although a conversion to drip irrigation may be considered. In any event, this analysis assumes that efficiencies among the various types of sprinkler systems are approximately the same and conversion between types is not included. The reduction in deep percolation can be written from Equation 90:

$$\Delta D_p = (1-\Delta AE)D_a \quad \ldots\ldots\ldots\ldots \quad (91)$$

in which ΔD_p is the reduction in deep percolation, mm; and
ΔAE is improvement in application efficiency expressed as a fraction.

The deficiently watered area (A_D) is given by:

$$A_D = \frac{D_r - Y_{min}}{b} \quad \ldots\ldots\ldots\ldots \quad (92)$$

Figure 34 shows hypothetical curves of A_D and application efficiency for several values of UCL. In addition, this information can be used to develop a linear irrigation scheduling relationship between the depth of required water and the length of irrigation (time) for a given application efficiency. This is given by the relationship:

$$\text{Length of Irrigation} = \frac{[Y_{min}+(1-D_r)]\,(\text{depth of required water})}{\text{application rate}} \quad (93)$$

where $Y_{min}+(1-D_r)$ is used as the fractional amount of required water($D_r \leq 1$), and the application rate is the average of the sprinkler system. The required water is defined as the amount (depth) necessary to fill the root zone plus the necessary leaching fraction. This relationship is shown in Figure 35 and would be for a specific sprinkler system. As can be seen from this graph, there is a "policy space" between the lines. The upper line has a higher efficiency (and a greater areal deficit) than the lower line which is the lowest practical efficiency at which a system should operate (no areal deficiency). A balance must be attained between the agronomic requirements of 0 percent of the area deficiently watered and the goals of an irrigation return flow control program which desires to decrease deep percolation and increase application efficienies to 50 percent or 100 percent areal deficit level. The relationships of application efficiency and UCL for various areal deficit levels is illustrated in Figure 36a.

Willardson et al. (1977) and others have stated that due to variations in wind and other factors, variations which occur in a single irrigation often tend to be compensated for by subsequent irrigations. Therefore, it is possible, and often desirable, to operate the sprinkler system in deficit ranges. The percent value of this deficit is difficult to ascertain, but is probably near 10 percent. In addition, there are managerial tools which can greatly increase application efficiencies. For example, Willardson et al. (1977) have shown that moving sprinkler heads by one-half of the distance between adjacent sprinklers each

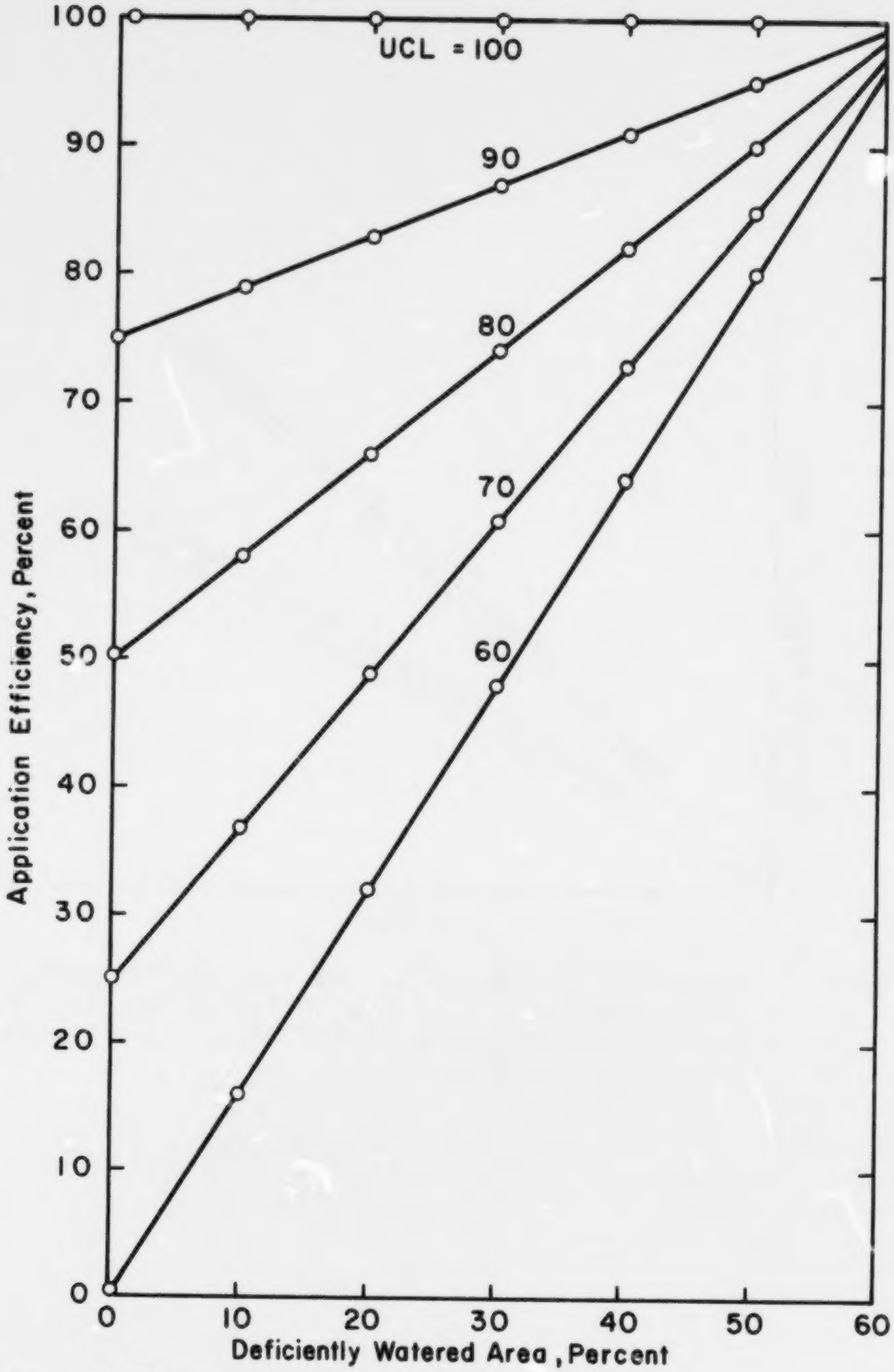


Figure 34. Deficiently watered area in percent.

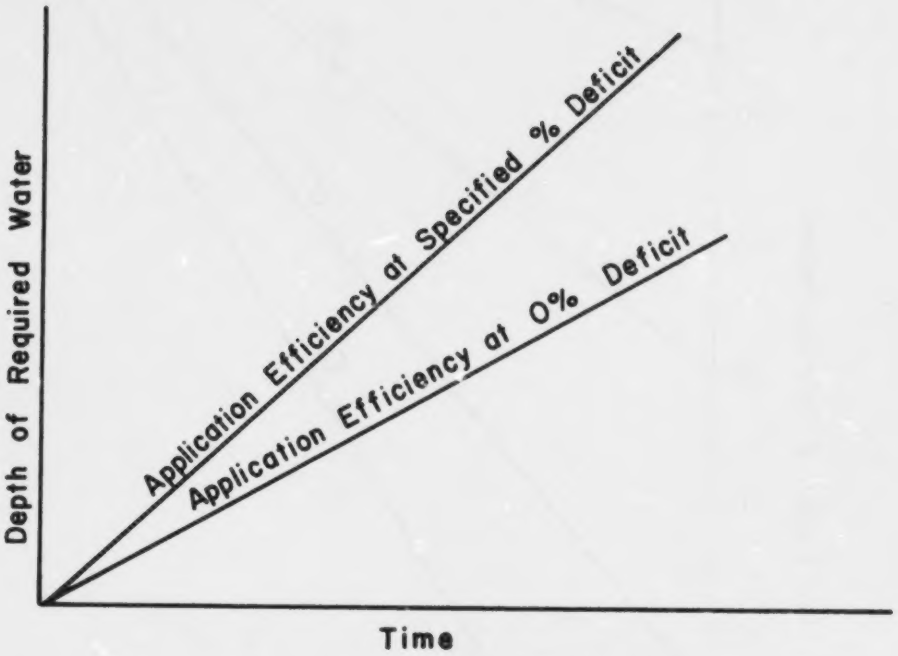


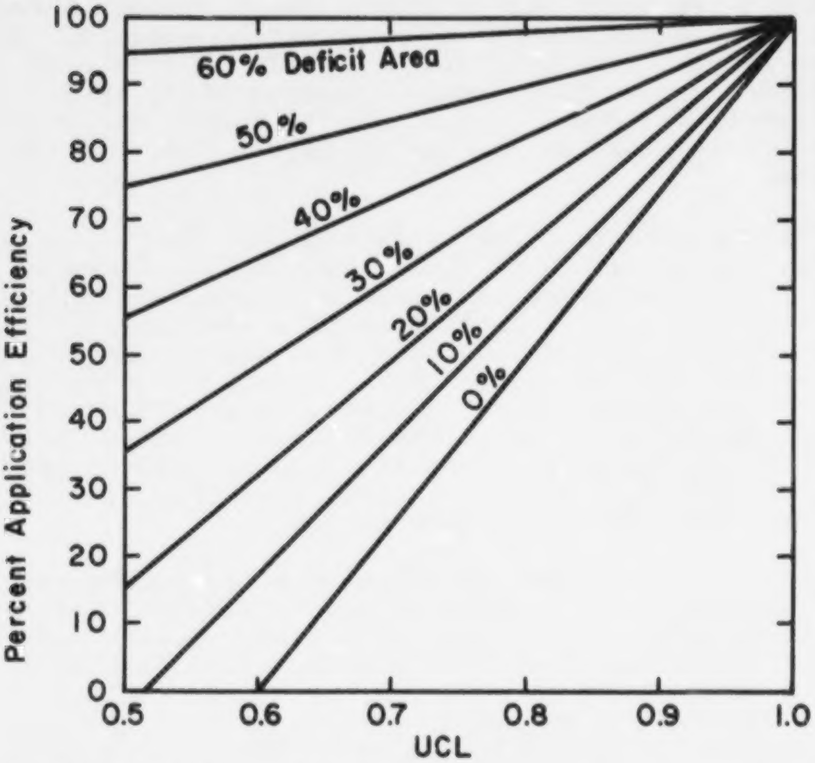
Figure 35. Hypothetical graph of the depth of required water for constant application efficiencies as a function of time for a given distribution coefficient.

irrigation, can increase seasonal uniformity by 5 percent. The percent increase in application efficiencies at various areal deficit levels in response to 5 and 10 percent increases in the UCL is shown in Figure 36b. The importance of this is illustrated by the following example. If an increase of 2.5 percent in application efficiency (5 percent increase in UCL) could be obtained at the 50 percent deficiency level, it would be equivalent to an increase of up to 12.5 percent at the 0 percent deficiency level (from Figure 36b). The 0 percent level is the level at which most growers would prefer to operate. Management practices which increase uniformity would have more of an impact at the higher application levels, demonstrating that a workable balance can be reached. Similar relationships can be determined for any deficit level by the use of Figure 36a, plotted as in Figure 36b.

The above example illustrates the fact that after the irrigation system is designed with as high a uniformity as possible, it is the management that ultimately determines the final efficiency. The irrigator decides what deficiency level is desired for agronomic purposes and then imposes additional management tools on the system such as irrigation scheduling and movement of sprinkler heads. However, it should be pointed out that many managerial alternatives do require additional labor and would not be implemented unless the marginal cost of water, or the cost of pollution control reflected in the water cost, was greater than the additional cost of labor.

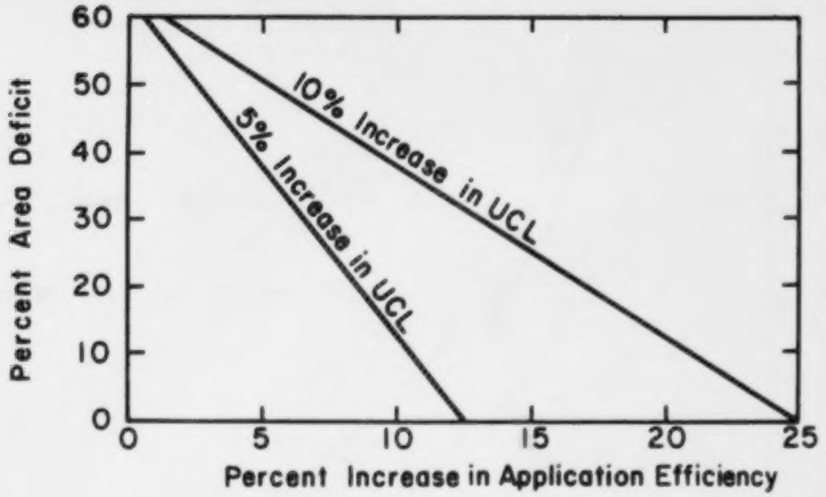
Obviously, the higher application efficiencies are desirable from the standpoint of irrigation return flow quality control. The relationship of application efficiency to salt pickup per irrigation, which could also be viewed as the deficit irrigation level as a function of salt pickup, is shown in Figure 37. This relationship does not appear to be sensitive to changes in evapotranspiration rates, but is affected by the quality of applied water. This curve was calculated from experimental data on a per irrigation basis because efficiencies, especially in surface irrigations, will change from one irrigation to the next (as is illustrated in Section 5: Present Irrigation Practices). Sprinkler application efficiencies, however, tend to be fairly consistent over the irrigation season, varying less than 10 percent on the average as compared to a seasonal difference which can be as much as 70 percent for surface irrigations in the Grand Valley, depending on the crop.

An examination of Figures 36a and 37 reveals that sprinkler systems with a UCL of 80 percent operating at the 50 percent areal deficit range would have a 90 percent application efficiency, and an average salt pickup contribution of 0.2 metric tons per hectare per irrigation due to deep percolation (500 mg/ℓ water). Over six irrigations, this would contribute only



a) Application efficiency as a function of the UCL.

Figure 36. Application efficiency as a function of the UCL, and the increases in application efficiency as a result of 5 and 10 percent increases in the UCL as related to the deficiently watered area.



b) Increase in application efficiency for 5 and 10 percent increase in the UCL as a function of the deficiently watered area.

Figure 36. (Continued).

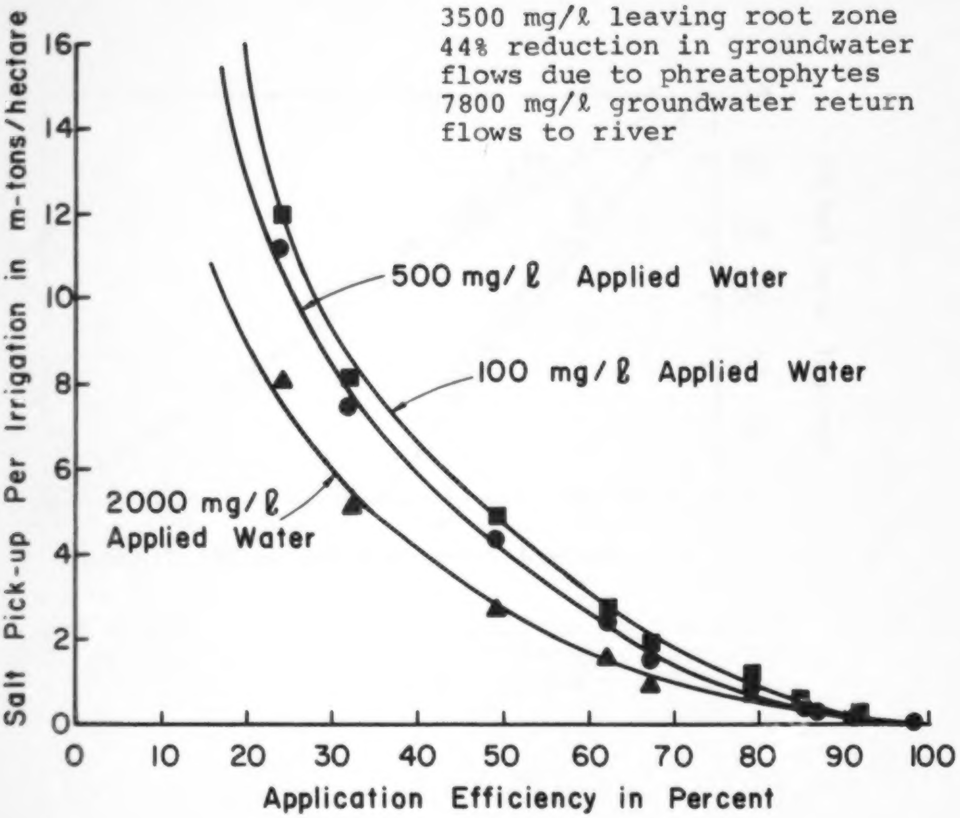


Figure 37. Relationship between salt pick-up and application efficiency as a function of the quality of applied water for the Grand Valley.

1.2 metric tons per hectare. The same system operation at a 0 percent areal deficit level would have an application efficiency of 50 percent and an average salt pickup contribution of about 4.5 metric tons per hectare per irrigation. This efficiency over six irrigations would contribute 27 metric tons per hectare. The same system operating at the 10 percent areal deficit level would have an application efficiency of 58 percent and a 2.7 metric ton per hectare per irrigation salt pickup for a total of 16.2 metric tons per season. This compares with present surface irrigation methods in the Grand Valley, which when combined with the data presented in Figure 21 (Section 5), results in salt pickup ranging from 20 to 30 metric tons per hectare per year due to deep percolation and head ditch seepage. Head ditches would be eliminated under sprinkler systems.

It should be obvious from the above discussion that management plays a very significant role in the salt contribution of any system, even potentially efficient systems such as sprinklers. In other words, the installation of an efficient system by itself will often not substantially reduce salinity in return flows.

EVALUATION OF SPRINKLER IRRIGATION IN GRAND VALLEY

Under this project, two sprinkler systems were installed and evaluated for salinity control effectiveness in the Grand Valley. These systems were a 5.2 hectare (12.8 acre) permanent overhead sprinkler system installed on a mature pear orchard and a 4" (10 cm) diameter side-roll wheel-move sprinkler on a 4.05 hectare (10 acre) established alfalfa field. In addition, the USDA Agricultural Research Service has just completed a series of studies using a center-pivot sprinkler system in the Grand Valley (Duke et al., 1976). The center-pivot method was chosen by the ARS primarily for the high degree of water application control which was afforded and not so much for the evaluation of center pivots in the Grand Valley.

Past experience with improperly designed sprinkler irrigation systems in the valley has caused a negative reaction among local growers. As a consequence, there are few agricultural sprinkler systems in the area.

The only overhead sprinkling system installed on an orchard in the Valley was constructed as part of this project. Approximately 10 percent of the irrigated area in the Valley is in orchards, and when irrigating pome and deciduous fruits, overhead sprinklers offer many advantages over conventional surface irrigation in addition to the obvious salinity benefits. These systems can be used for cooling, frost protection or bud retardation, and fertilizer and pesticide applications.

The grower who owns and operates this system has been quite pleased with the results. In the spring of 1976, the harvest on the part of his orchard not under this system was small due to frost damage; the frost protection abilities of this system saved the 5.2 hectares of pears and a full crop was harvested. In such cases where the gross income from the crop is in excess of $2,500 per hectare ($1,000 per acre) per year, it is obvious that potential savings can be substantial, and the system could almost pay for itself in one year.

This system was installed for a total cost of $3,432 per hectare ($1,389 per acre) in the spring of 1975. During the two years the system was evaluated, the annual operation and maintenance costs were less than $185 per hectare ($75 per acre) including frost protection, irrigation, and some cooling.

Taking into consideration the pressure differential from the top and the lower end of the field, the average application rate for the system was 3.23 mm/hr (0.127 inches per hour) when the entire field was in operation at once as in frost protection. When only half the field was being irrigated at one time, the application rate was 4.17 mm/hr (0.16 inches per hour), and when a fourth of the field was in operation, the application rate was 4.39 mm/hr (0.173 inches per hour). The UCL was 86.3 percent (UCC = 89.0, UCH = 88.5). An examination of the catch-can data plotted on Figure 38 reveals that the line does not pass exactly through $X = 0.5$ at $Y = 1.0$ as it should theoretically. This is due primarily to the effect of canopy interference on measurements. This also partially accounts for the low r^2 value of 0.874.

Figure 39 illustrates the application efficiencies which could be expected at various levels of water management or levels of deficit applications. Figure 40 presents irrigation scheduling curves for the three different application rates. This system was designed with four values so that, if necessary, the system could be operated in fourths or multiples thereof providing a large amount of flexibility in the operation and management of the system.

An evaluation of Figure 37 and Figure 39 in combination indicates the salt pickup of this system operating at the 0 percent deficiency level contributes about 2.5 metric tons per hectare per irrigation. For seven irrigations, this would produce 17.5 metric tons per hectare per season. At the 10 percent deficiency level, the system would contribute 14 metric tons per hectare per season at the 20 percent deficiency level, it would contribute about 7 metric tons per hectare, and at the 50 percent deficiency level about 1.4 metric tons per hectare per season. Therefore, a workable balance between the goals of salinity control and crop yield could probably be achieved at the 10 to 15 percent areal deficit level.

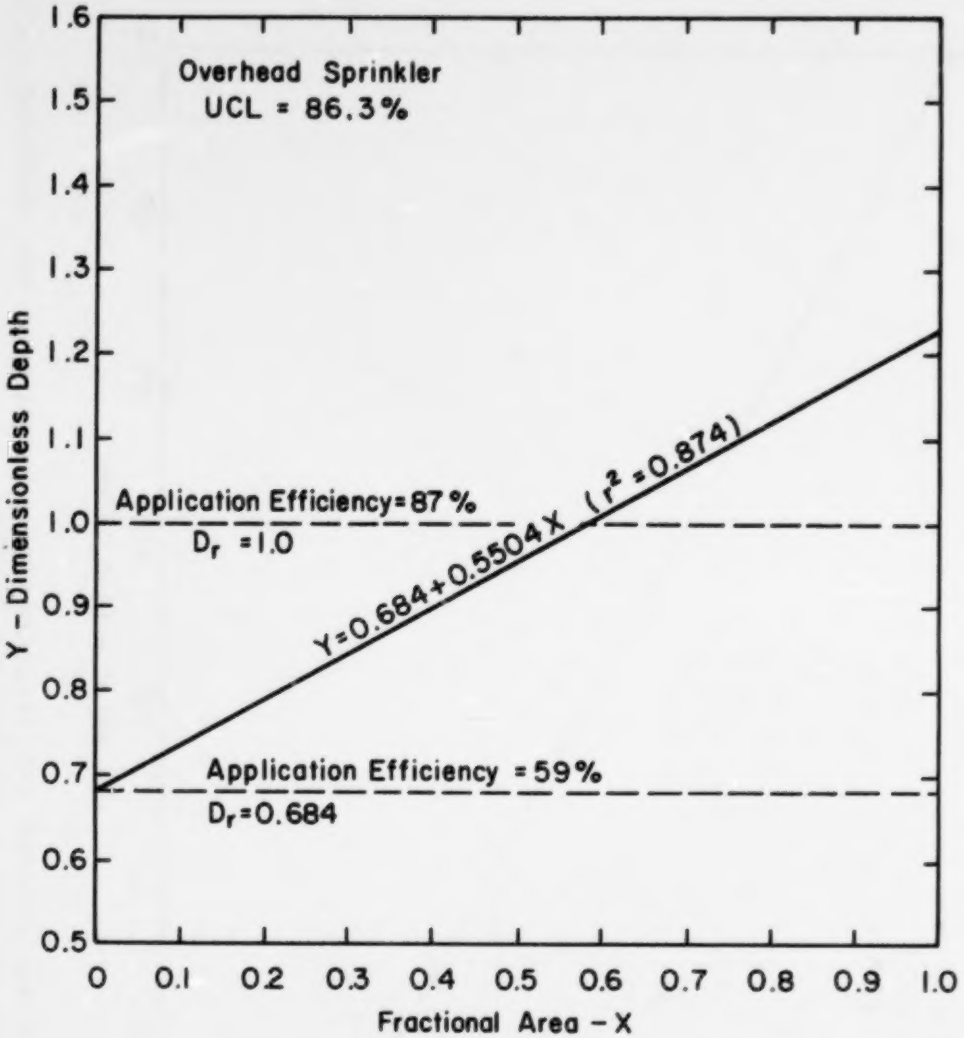


Figure 38. Distribution characteristics of the 5.2 hectare overhead sprinkler system.

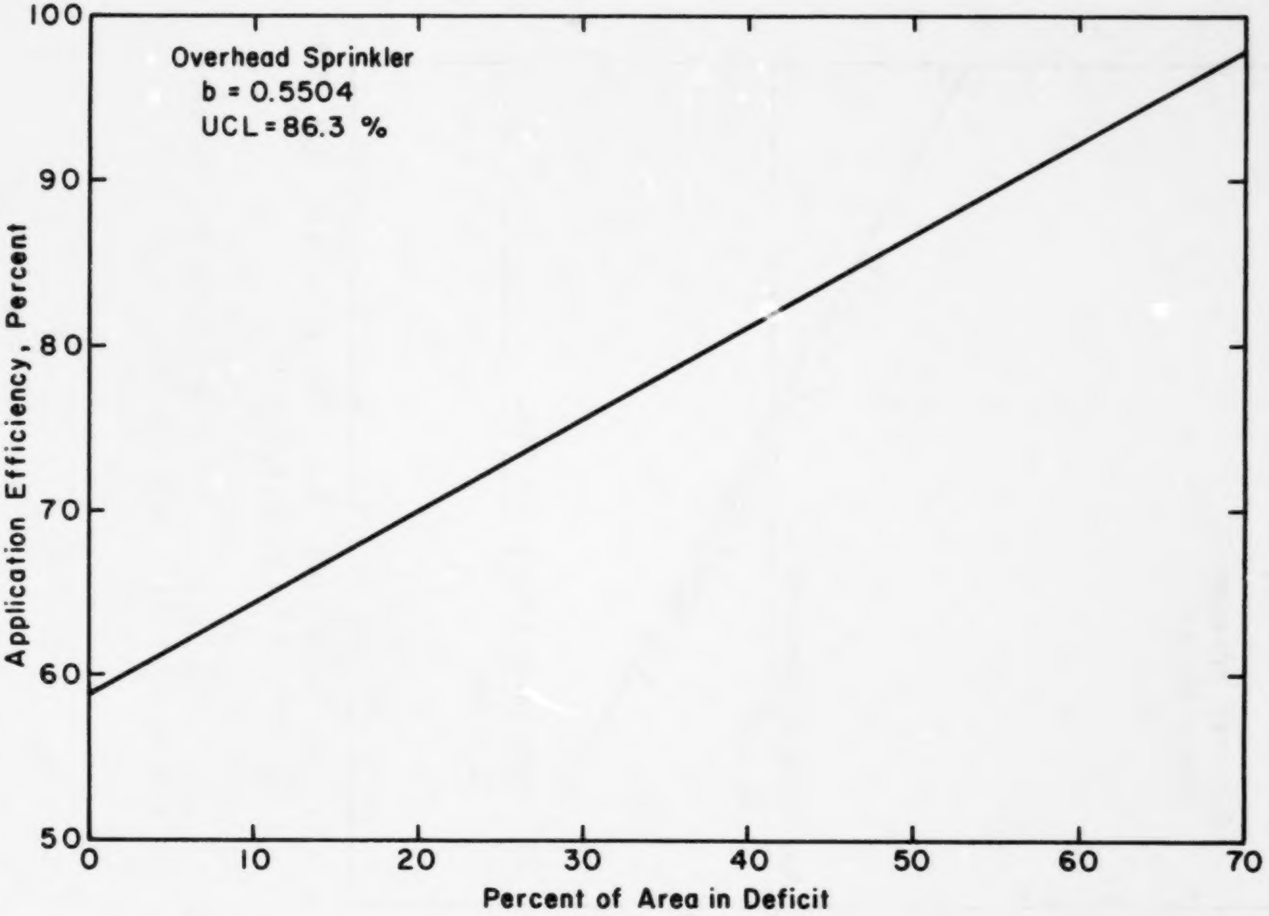


Figure 39. Expected application efficiencies for operation of the overhead sprinkler system at various areal deficit levels.

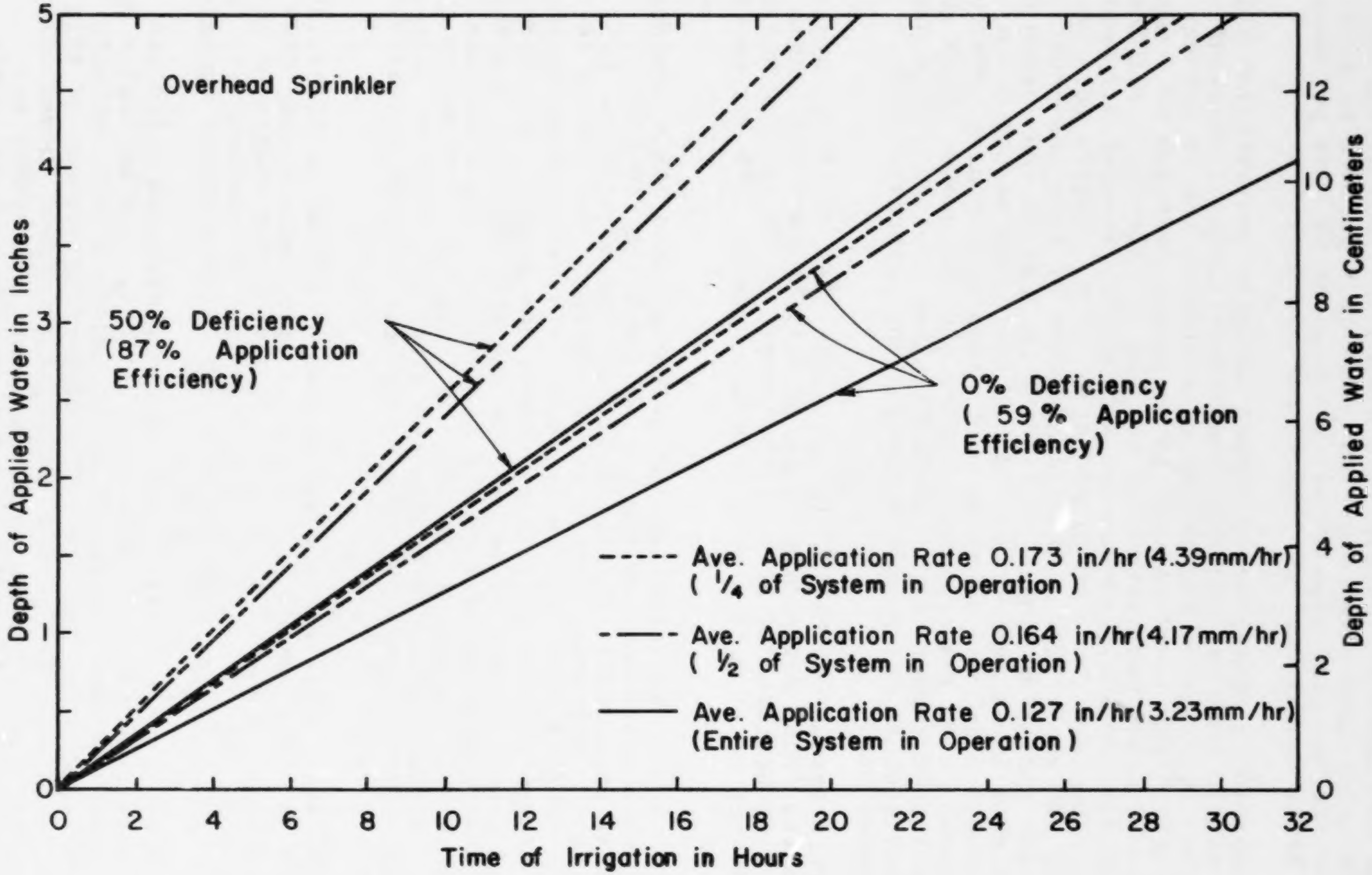


Figure 40. Irrigation scheduling curve, at the different·application rates, for the overhead sprinkler system.

As mentioned previously, the system cost was $3,432 per hectare which discounted over ten years at 8 percent is $512.40 per hectare per year plus annual O & M costs of $185 per hectare for a total annual cost of $697.40 per hectare.

Assuming a conservative annual salinity contribution value of 20 metric tons per hectare under conventional irrigation methods, operation of the sprinkler system at the 10 percent areal deficiency level results in an annual decrease of 6 metric tons per hectare per season due to deep percolation. Elimination of head ditches would reduce the salinity by another 2.2 metric tons per hectare for a total reduction of 8.2 metric tons per hectare per year. The cost-effectiveness of this permanent solid-set sprinkler system is $418.54 per metric ton (using only the initial investment costs and not including annual O & M). Even though this cost is quite high, this system does offer many advantages other than salinity control to the grower which should be considered such as frost protection and cooling. This analysis does not account for annual depreciation, interest, taxes, insurance, etc.

This system was higher in cost than most solid-set systems due to its frost protection capabilities. A more reasonable cost for a 4.05 hectare (10 acre) system would be $2,915 per hectare ($1,180 per acre) with a cost-effectiveness of $356 per metric ton.

The second sprinkler system evaluated under this project was a side-roll wheel-move system on 4.05 hectares (10 acres). Figure 41 represents the uniformity and the application efficiencies for different levels of management. The UCL is 86.7, the UCC is 89.5, and the UCH is 88.8. Figure 42 presents the curve of application efficiency versus the present deficiently watered area. It should be pointed out that Figures 39 and 42 are almost equivalent due to the closeness of their uniformity coefficients. Figure 43 depicts the irrigation scheduling curves for the system. There are only two lines presented on this graph because, unlike Figure 40, this system can only be operated one set at a time.

The total cost of this system was $7,830.64 or $1,933.49 per hectare ($783.06 per acre), or $288.15 per hectare when discounted at 8 percent for ten years. The annual operation and maintenance cost (O & M) has been $128.50 per hectare ($52 per acre), resulting in total annual costs of $416.65 per hectare.

An analysis similar to that for the overhead solid-set sprinklers reveals that the side-roll wheel-move sprinkler system would likewise have the potential to reduce annual salinity by 8.2 metric tons per hectare. The cost-effectiveness of this system is $236.00 per metric ton of salt removed, based only on the capital cost of the system. However, the system was installed on a small field and could be expanded at little

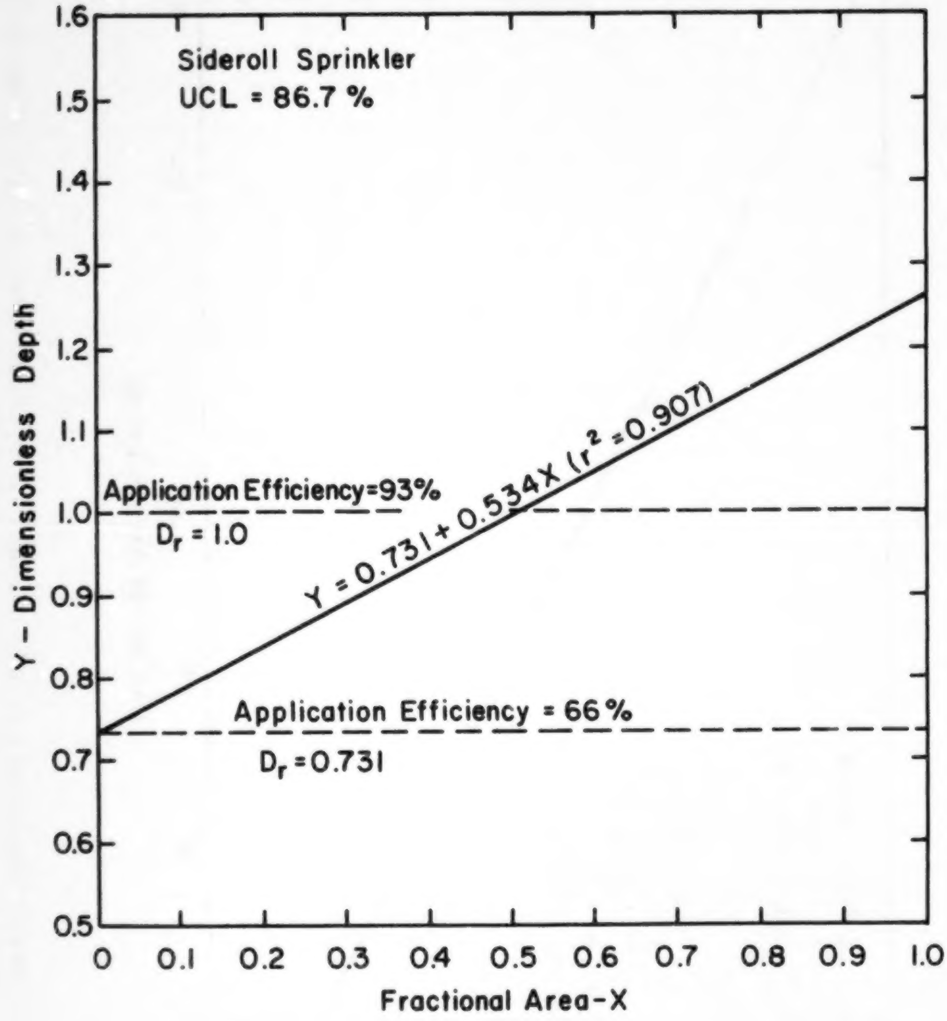


Figure 41. Distribution characteristics for the 4.05 hectare side-roll wheel-move sprinkler system.

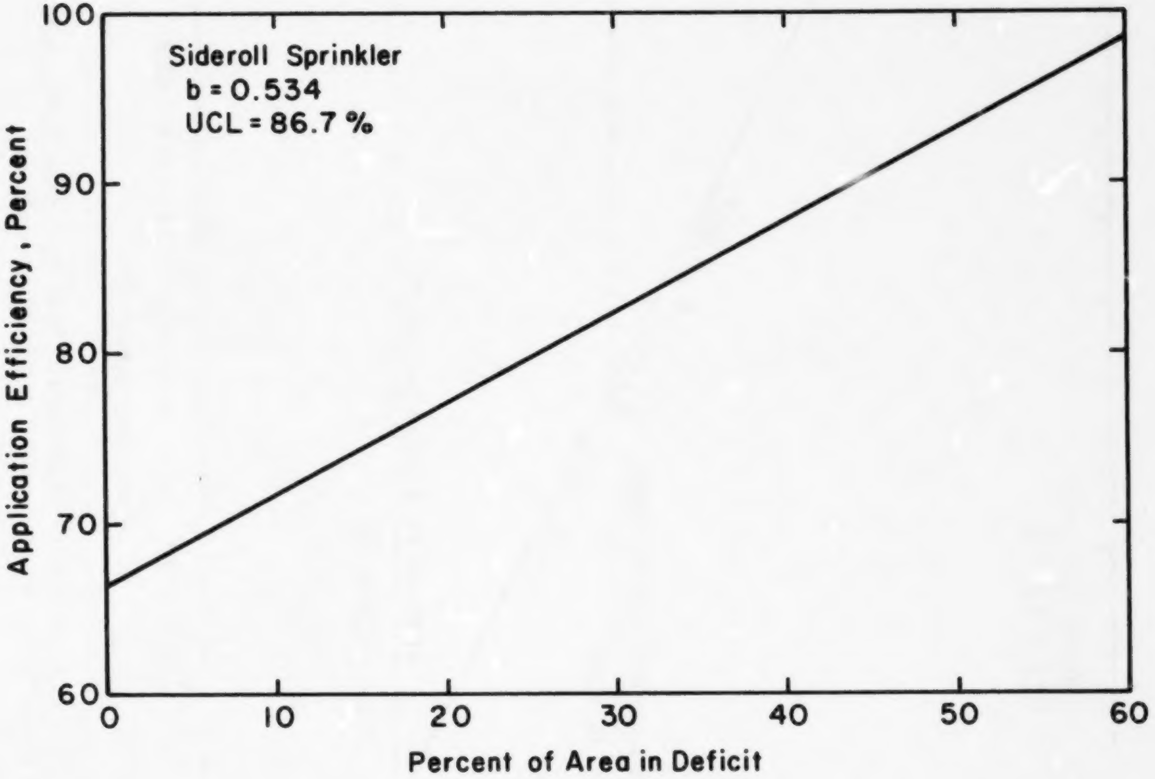


Figure 42. Expected application efficiency for operation of the side-roll wheel-move sprinkler system at various areal deficit levels.

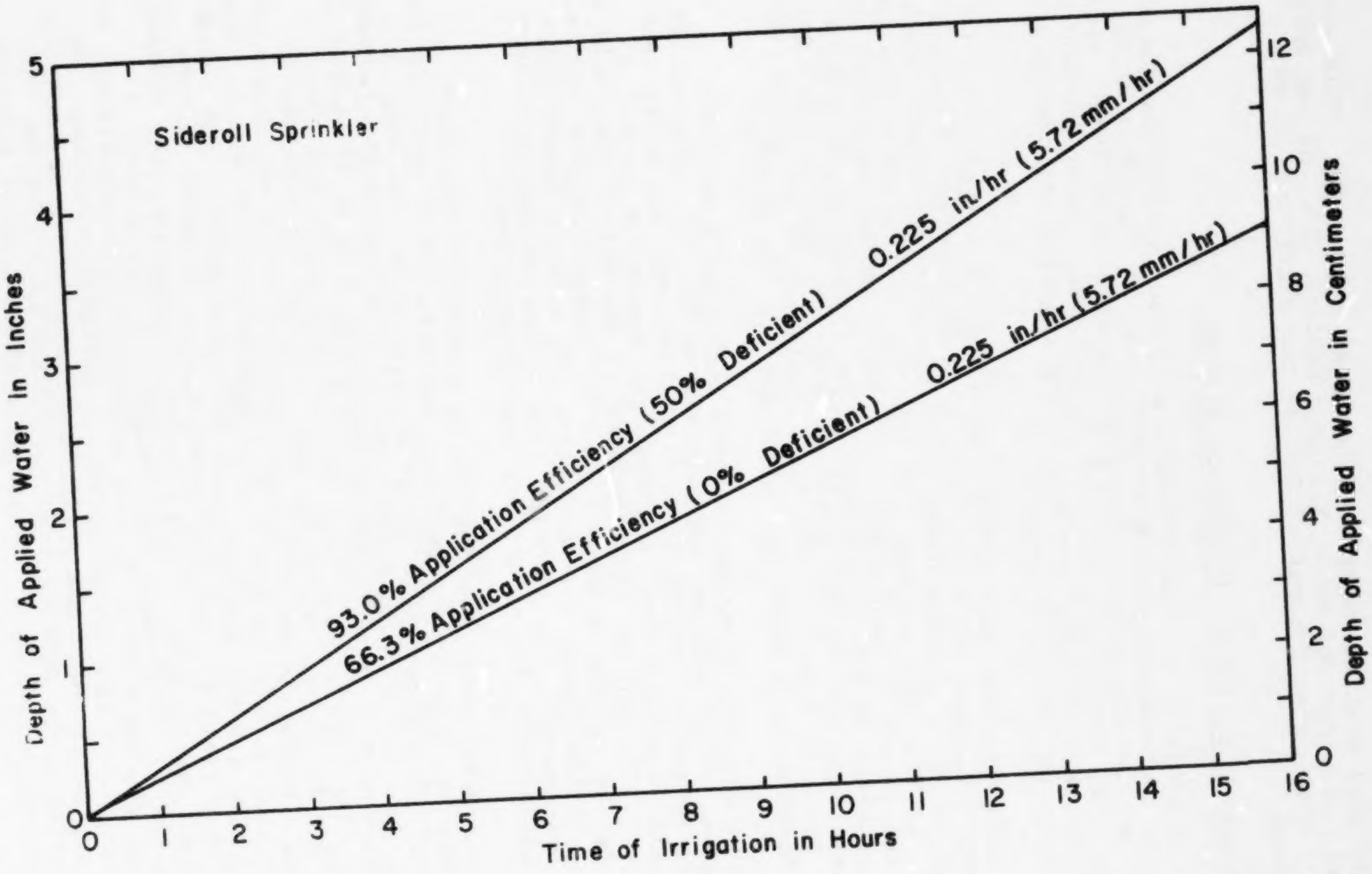


Figure 43. Irrigation scheduling curves for the side-roll wheel-move sprinkler system.

additional cost to cover 16.2 hectares (40 acres). This would result in a cost of about $750 per hectare ($303.50 per acre), and a cost-effectiveness of $ 91.46 per metric ton of salt removed.

Alternative Sprinkler Irrigation Systems

In addition to the permanent solid-set sprinklers and the side-roll wheel-move sprinkler evaluated in the Grand Valley, there are several other commercially available sprinkler systems which could potentially be used in the area. These include hand-move portable systems, portable solid-set systems, center pivots, traveler, and tow-line systems.

Hand-move portable systems were the first type of sprinkler systems developed and still enjoy wide popularity. They are usable in any situation where other types of sprinklers can be used. As the name implies, the laterals of the system are moved from set to set by hand labor. The mainline may be either buried and permanent or may be portable. The approximate cost of a complete hand-move system would be $650 per hectare ($260 per acre) for a 16.2 hectare (40 acre) field, plus, of course, the considerable labor requirements to operate the system.

Portable solid-set systems are basically a portable hand-move system with enough laterals so that the laterals do not have to be moved. In the Imperial Valley they are often used to germinate vegetable crops and then the system is removed to another field; and for the remainder of the season the field is irrigated by surface methods. In other areas they are removed at the end of the season for harvesting and tillage operations. These systems are only slightly less expensive than permanent solid-set systems due to smaller installation costs.

Many means have been devised to circumvent the labor requirements of hand-move portable systems, one of which is the center-pivot system. This sprinkler system rotates about a central point (pivot) in a large circular or elliptical pattern and most commonly covers 55 to 61 hectares (135 to 150 acres) per system. The water is supplied through the pivot, and the sprinklers are spaced along the pipe. The water application rates on a center-pivot system vary from very low at the center to very high at the end due to areal coverage differences. These systems have several disadvantages. As one example, the corners of a square field are not irrigated, unless by other systems because of the circular pattern, and, consequently, the systems are limited to areas where land values are fairly low. In addition, the water distribution efficiencies (uniformities) are often much lower than other sprinkler irrigation systems. On some heavy soils where the application rate is higher than the infiltration rate, erosion from runoff can be a problem. In addition, on heavy soils, the machines often develop traction problems. Due to the heavy soils and small fields of the Grand Valley, center pivots are not currently recommended. These systems cost in the vicinity of $976 per hectare ($395 per acre) for 55 hectares (135 acres) not including a well. The uniformity and application efficiencies analysis used in this section should not be applied to center-pivot irrigation without modification of the procedures.

Traveler or "big-gun" systems are usually limited to soils with high infiltration rates since the sprinkler head is essentially a large volume outlet "shooting" a large volume of water up to 60 meters (200 feet) or more. The sprinklers can move down a lane in the field on a trailer arrangement and pulling a long flexible hose while irrigating, hence the name traveler. "Big-gun" sprinklers can also be mounted on permanent towers, thus becoming a high volume permanent solid-set system.

There are several variations on the traveler design including a traveling boom type of system which uses several smaller sprinklers mounted on a large boom to cover approximately the same area. Traveler systems have many of the same disadvantages of center-pivot systems, although instead of losing land at the corners of a field, land is lost in the travel lanes every 46 to 122 meters (150 to 400 feet). For many of the same reasons, traveler or "big-gun" systems are likewise not suitable for the Grand Valley at this time. Approximate average total costs for a traveler system are in the range of $660 per hectare ($240 per acre) for a 16.2 hectare (40 acre) field.

Another type of sprinkler system quite similar to the side-roll wheel-move concept is the end-tow or tow line. As the name indicates, the system is mounted on skids or wheels, but is towed from the end to the next set by a tractor or other vehicle. These systems cost approximately $555 per hectare ($225 per acre) for a 40 acre field. However, they are limited to fairly large fields because they are towed forward to the next set and back to the next in a zig-zag pattern. Consequently, these systems would not be adaptable to the small field situations found in the Grand Valley.

SECTION 11

TRICKLE IRRIGATION

DESCRIPTION

A survey conducted in 1975 indicated that there were 54,115 trickle (or drip) irrigated hectares (133,717 acres) in the United States (Shoji, 1977). It was also estimated that there would be more than 200,300 trickle irrigated hectares (495,000 acres) in the U.S. by 1980. A more recent survey conducted in late 1976 found that California alone presently has 50,200 hectares (124,000 acres) of trickle irrigated crops (Irrigation Journal, 1976).

Trickle irrigation is a system whereby water and possibly fertilizer are applied directly to individual plants, as opposed to irrigating the entire field area as with surface or sprinkler irrigation. For orchard crops and other widely spaced crops, this is accomplished with small diameter "laterals" running along each crop row. "Emitters" attached to the lateral supply each plant with its water needs. In the case of row crops or truck crops, products are available with small diameter laser-drilled orifices spaced at regular intervals along a thin-wall hose, commonly referred to as "emitter-hose".

With trickle irrigation, water may be provided to the crop on a low-tension, high-frequency basis, thereby creating a near optimal soil moisture environment. Because of the high irrigation frequencies, very high water use efficiencies are possible. Water use efficiency as used in this report is defined as the crop yield per unit of applied water. Research indicates that water use efficiency can be increased by 50 percent or more using trickle irrigation as compared with surface irrigation (Hiler and Howell, 1972).

Because only the plants' root zone is supplied with water, under proper system management little water is lost to deep percolation, consumption by nonbeneficial plants, or soil surface evaporation. Wierenga (1977) reported that trickle irrigation increased cotton yields by more than 8 percent while using 24 percent less applied water as compared to surface irrigation. Trickle irrigation was also effective in controlling the return flow volume and in maintaining relatively low salinity levels in the soil adjacent to the emitters.

In addition to reduced water requirements and minimization of return flows, trickle irrigation has other positive advantages. These include: (a) relatively saline water may be used under proper management; (b) sloping or irregularly shaped land areas may be more easily irrigated; (c) sandy soils may be more efficiently irrigated; (d) increased production with most crops is documented; (e) irrigation labor requirements are reduced; (f) insect, weed, and disease problems are often reduced; (g) soluble fertilizers and possibly pesticides and carbon dioxide may be applied through the system; (h) harvesting and tillage operations may occur simultaneously with irrigation; (i) systems may be easily automated; and (j) the practicality of using low-yielding wells is increased. Also, there is potential for using sewage or processing effluent water as a water source.

A wetted profile develops in the plants' root zone beneath each emitter or emitter-hose orifice. The shape of the profile is dependent on various soil characteristics and is limited by horizontal flow constraints of the soil. An idealized version of this profile for a tree crop is shown in Figure 44.

The surface area between widely spaced plants and between plant rows is dry, receiving moisture only from rainfall. Because of this, weed control problems may be substantially reduced and it is possible to have virtually weed-free orchards.

A trickle irrigation system consists of a system "head" and a distribution network. A pump, filter, flow meter, pressure gauges, fertilizer injector, valve, pressure regulator, and controller generally make up an automated system head as shown in Figure 45. The flow meter and fertilizer injector are optional equipment but highly desirable, and a controller is necessary only if the system is to be automated. Anti-surge valves are often necessary on larger systems.

The distribution network consists of piping, pipe fittings, emitters, and circuit valves. Valves are actuated electrically or hydraulically in the case of an automated system.

Drip systems are filtered either by a graduated sand filter or a screen filter. Both require periodic backflushing which can be automated. Either type filter may be preceded by a centrifugal separator capable of removing most of the relatively high density particles. Emitter manufacturers usually specify the degree of filtration required for their emitter.

Any water soluble fertilizer or other water soluble chemical may be injected into the trickle system. A pressure differential can be used to cause flow through a tank as indicated in Figure

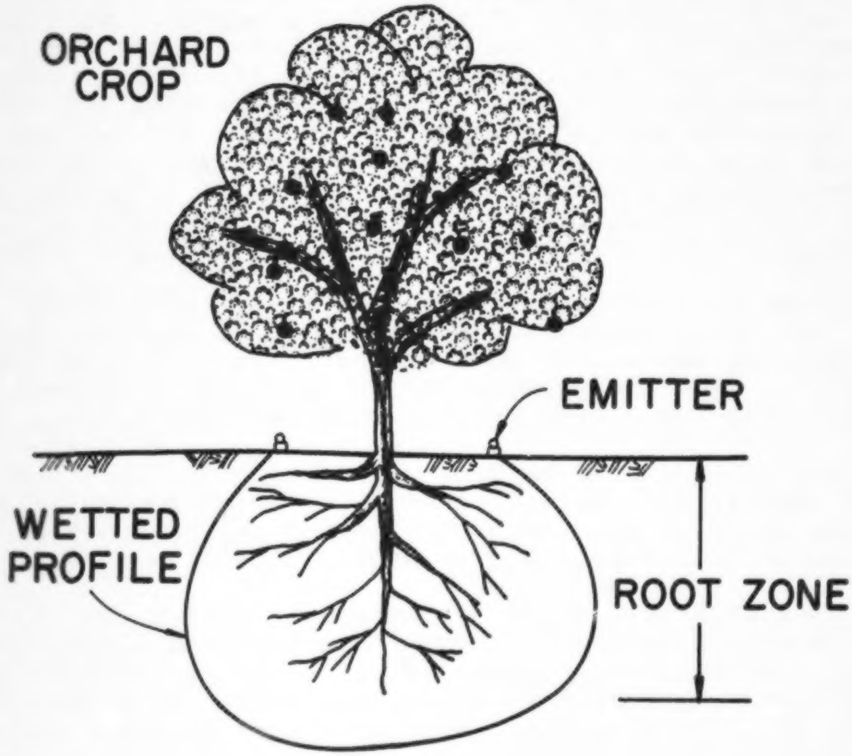

ORCHARD CROP
EMITTER
WETTED PROFILE
ROOT ZONE

Figure 44. A wetted profile develops in the root zone below each "emitter" or "trickler". This cross section illustrates an idealized profile below emitters placed on either side of a tree crop.

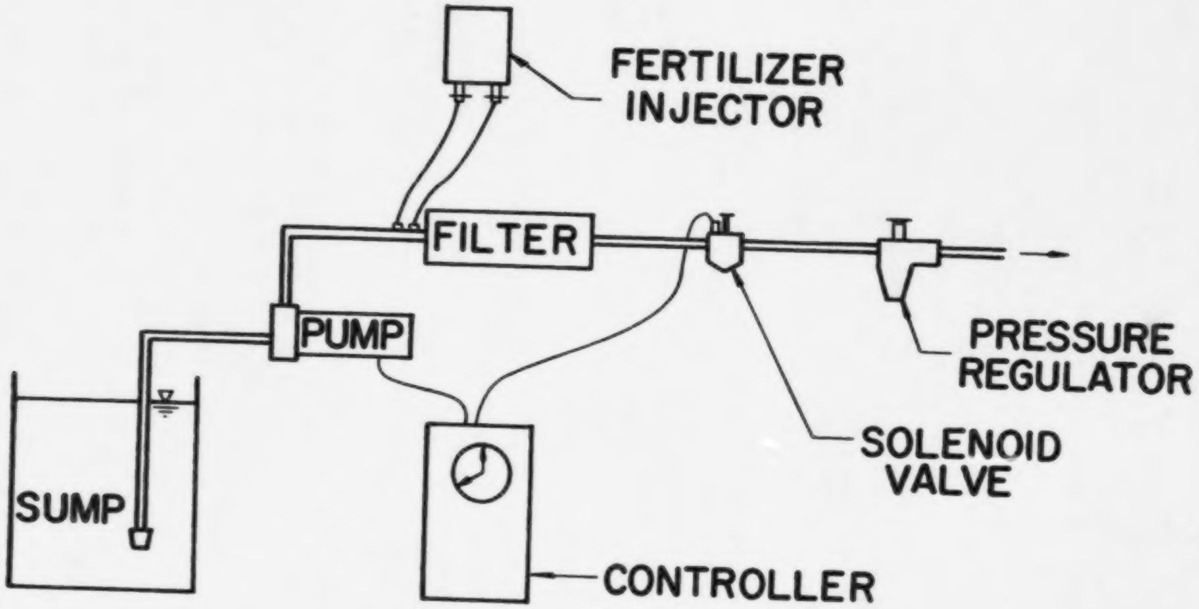

FERTILIZER INJECTOR
FILTER
PUMP
SUMP
CONTROLLER
SOLENOID VALVE
PRESSURE REGULATOR

Figure 45. Diagram of a typical automated, trickle system "head."

45, or a nutrient metering pump can be used to carefully control fertilizer applications. In either case, fertilizer is injected in advance of the filter so that any undissolved solids are removed and do not cause plugging.

Experience by California growers indicates that continuously injecting chlorine at a concentration of about one part per million is desirable for long-term system maintenance. On large acreages this can be accomplished most economically with a gas chlorinator. Also, additional chemical injection to control biological slime buildup in the laterals may be necessary.

Trickle systems operate at relatively low pressure as compared to sprinkler systems (5 to 20 psi or 35 to 140 kPa pressure compared to 45 to 100 psi or 310 to 690 kPa). For this reason, pumping requirements are substantially less than other pressurized irrigation systems. A pressure regulator is used to accurately control the lateral line operating pressure. Multiple pressure regulators may be desirable for locations with large elevation changes, and in some cases, low cost pressure regulators have been used at the head of each lateral.

Small diameter, polyethylene or polybutylene pipe is generally used for the system laterals which are laid on the soil surface along each crop row or are buried to facilitate tillage operations. Polyethylene pipe is available which is chemically resistant to ultraviolet radiation. The ultraviolet radiation causes some plastics to be subject to stress cracking, which has been a problem with untreated pipe.

The lateral is connected to a manifold which is supplied with water through a submain and/or main. A typical 6.1-hectare (15-acre) orchard layout is shown in Figure 46. Laterals usually run at right angles to the field slope. Manifolds, submains, and mains are usually buried with short risers supplying laterals laid on the surface.

A multitude of different types of emitters are available, the purpose of each being to cause a pressure drop so that only a small flow of water is discharged. This necessary head loss is accomplished through the use of orifices, vortices, torturous paths, impact plates, or a combination of these. The flow through a particular emitter is dependent on lateral pressure and may vary from as low as one liter/ hour (0.26 gallons/hour) to as much as 30 liters/hour (8 gallons/hour). Figure 47 presents pressure versus flow curves for a few selected emitters and emitter-hose products.

Basically, emitters may be classified into two categories. The "standard" emitter or dripper emits water as a small stream or drip which contacts the soil surface immediately below the emitter. An aerosol emitter (also known as foggers, spitters,

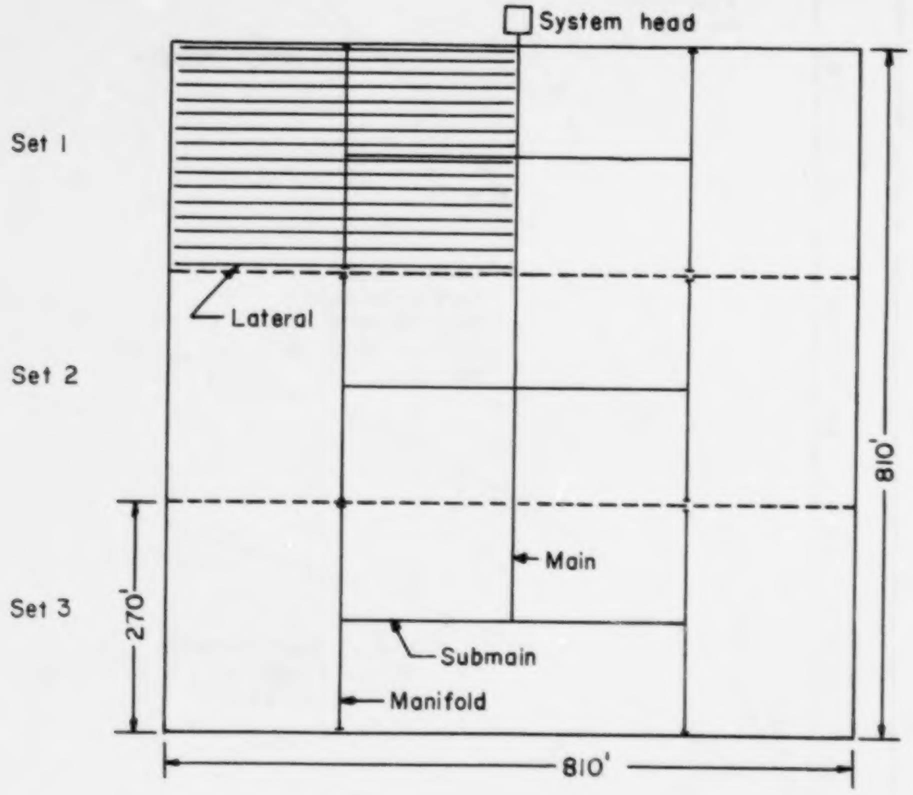

System head
Set 1
Set 2
Set 3
Lateral
Main
Submain
Manifold
270'
810'
810'

Figure 46. A typical 6.1-hectare (15-acre) orchard layout showing the various system components.

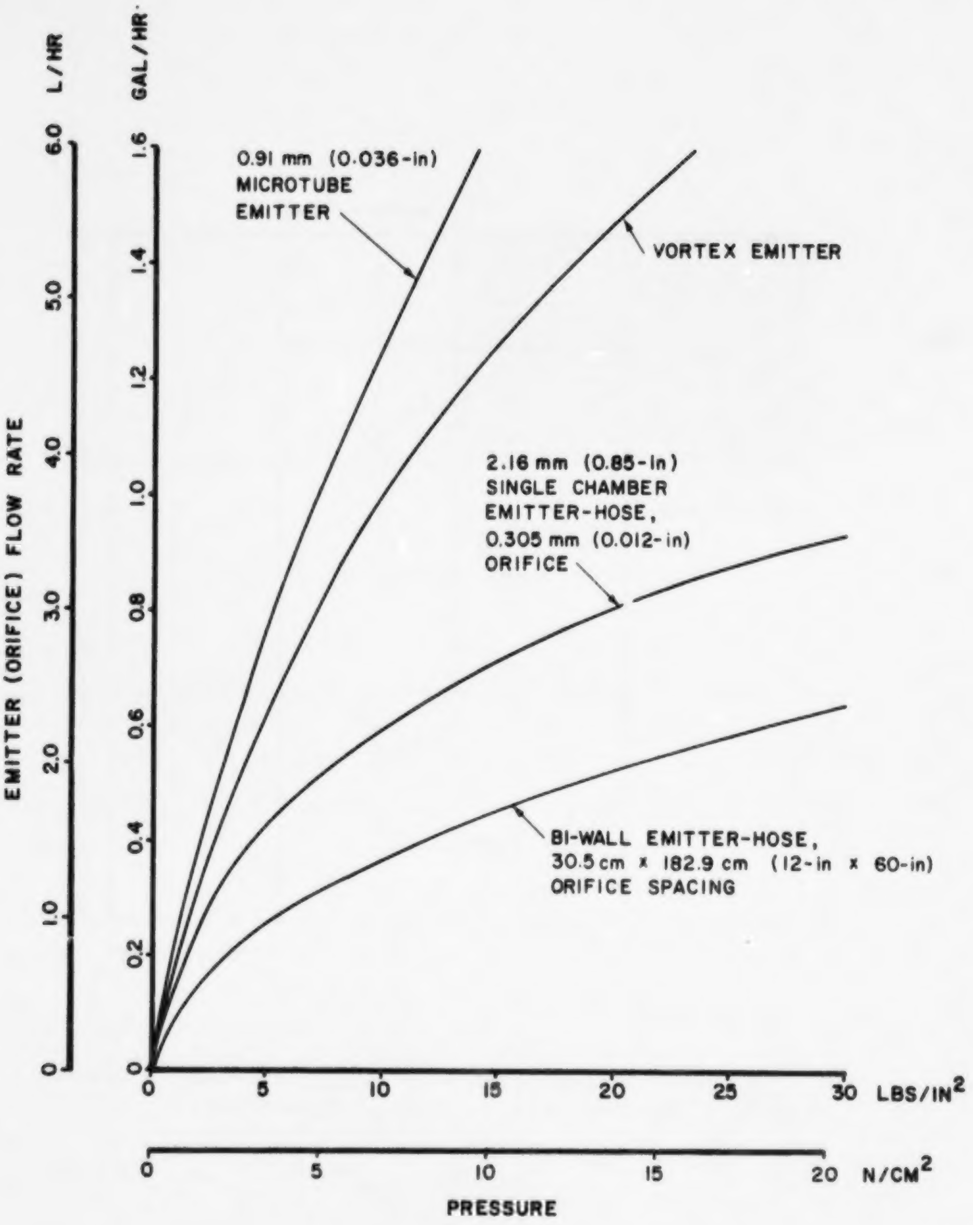


Figure 47. Pressure rating curves for selected emitters and emitter-hose products (Smith and Walker, 1976).

misters, and miniature spinklers) sprays water through the air for some distance before it contacts the soil surface. Figure 48 illustrates idealized soil moisture cross sections under a standard emitter and an operating aerosol emitter. Note that saturated conditions are probable under the standard emitter. This condition can inhibit root development due to limiting aeration, but the obvious disadvantage of the aerosol emitter is increased evaporation losses to the air during emitter operation and from wet soil surfaces. Additional descriptive materials and research findings for various crops, etc. may be located in Smith and Walker (1975), an annotated bibliography on trickle irrigation.

EMITTER HYDRAULICS

Over the desired range of discharges, the flow charactersitics of any emitter may be characterized by the power curve equation as presented by Keller and Karmeli (1975):

$$Q = a H^{b} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (94)$$

where Q = emitter discharge, lph
a = a constant of proportionality which characterizes each emitter,
H = the working pressure head at the emitter, meters,
b = the emitter discharge exponent.

To determine coefficients a and b, the discharges at two or more operating pressures must be known. The value of b characterizes the flow regime and discharge versus pressure relationship of the emitter. The lower the value of b, the less the discharge will be affected by pressure variation due to pipe friction or elevation changes. In the fully turbulent flow regime, b = 0.5, and in the laminar flow regime, b = 1.0. If an emitter could fully compensate for changes in operating pressure (i.e., a pressure compensating emitter), b would equal 0.0. Such an emitter does not exist although some are reasonably effective as pressure compensating emitters.

TRICKLE SYSTEM HYDRAULICS

A great deal of useful work has been done during the past decade toward refining the design procedures for trickle irrigation systems. The most noteworthy of the resulting publications include Keller and Karmeli (1975), Wu and Gitlin (1974), Wu and Fangmeier (1975), Howell and Hiler (1974), and Jobling (1974). In addition, Wu and Gitlin have published various design aids such as charts and slide rules through the Engineer's Notebook series, Cooperative Extension Service, University of Hawaii, Honolulu, Hawaii. Other references to design procedures, design

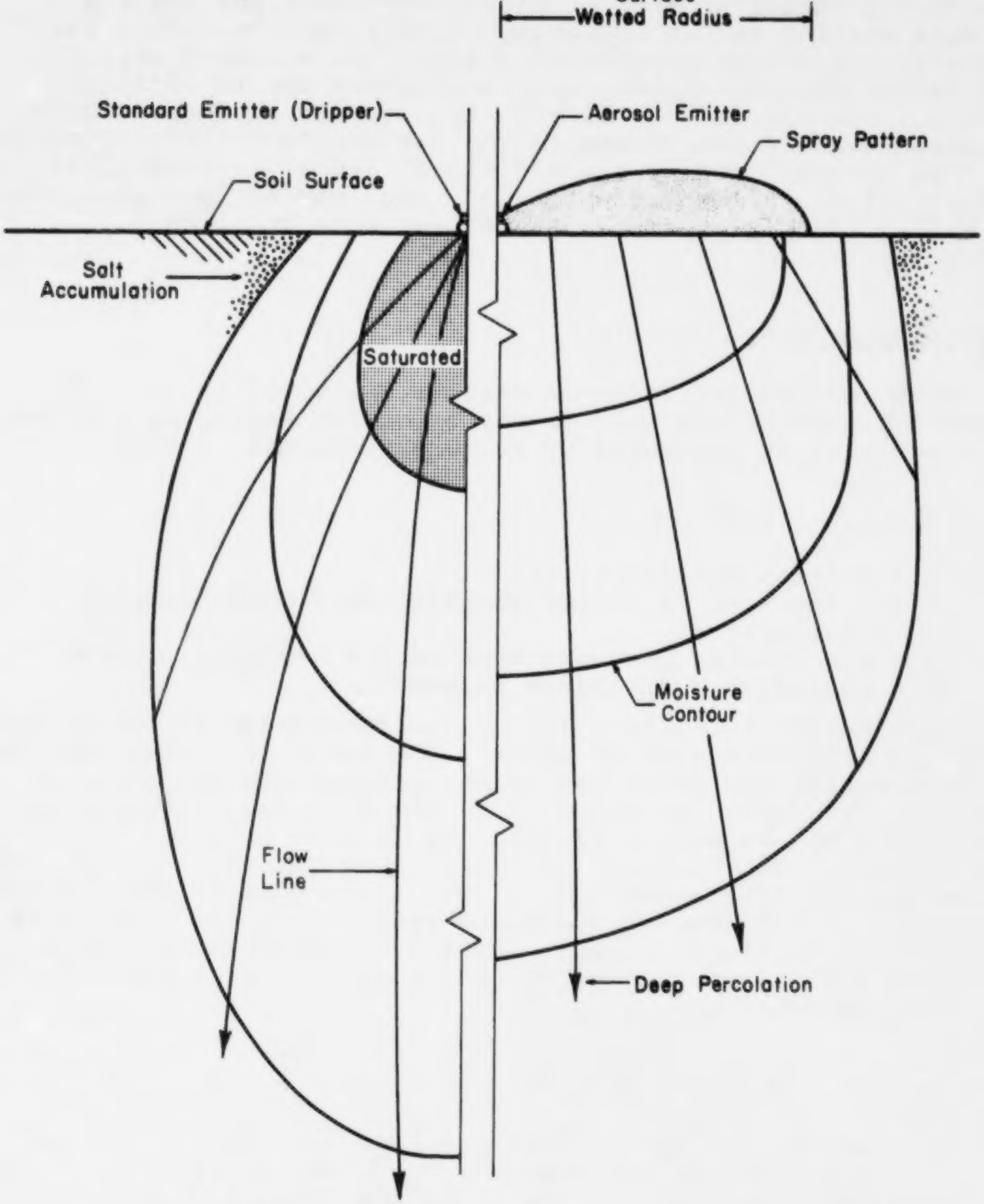

Surface
Wetted Radius
Standard Emitter (Dripper)
Aerosol Emitter
Spray Pattern
Soil Surface
Salt
Accumulation
Saturated
Moisture
Contour
Flow
Line
Deep Percolation

Figure 48. Idealized soil moisture cross sections under a standard emitter and an operating aerosol emitter. Equal flow rates from each are assumed (Karmeli and Smith, 1977).

parameters, uniformity criteria, etc. may be found in Smith and Walker (1975).

TRICKLE SYSTEM UNIFORMITY AND EFFICIENCY

An ideal trickle irrigation system would be one which exhibits a uniform discharge from every emitter in the system, resulting in uniform water application throughout the crop. Unfortunately, such a system is nonexistent primarily because of: (a) emitter characteristics including manufacturing variability; and (b) differences in pressure distribution throughout the pipe network due to frictional head losses (Karmeli et al., 1977). In addition, elevation changes, emitter clogging, and water temperature variation affect emitter discharge rates.

The variation in the value of the proportionality constant, a, in Equation 94 tends to be normally distributed about a mean value. Keller and Karmeli (1975) have developed a manufacturer's coefficient of emitter variation, v_m, which characterizes emitter flow rates at a given pressure head as a normal distribution:

$$v_m = \frac{\sigma}{\mu} \quad \ldots\ldots\ldots\ldots \quad (95)$$

where v_m = manufacturer's coefficient of emitter variation
σ = standard deviation of emitter discharges at a reference head
μ = mean discharge of emitters at a reference head.

Because of the normal distribution concept, 68 percent of an emitter sample group will have a discharge within ± one standard deviation of the mean, about 95 percent will have a discharge within ± two standard deviations of the mean, and 98 percent will have a discharge within ± three standard deviations of the mean.

Soloman (1977) evaluated a number of emitters which exhibited v_m's ranging from a low of 0.02 to a high of 0.40. As more emitters are performance evaluated over time, manufacturers will tend to improve their products.

Several studies have characterized the pressure distribution along a lateral line (Wu and Gitlin, 1974; and Keller and Karmeli, 1975). A rule of thumb was subsequently adopted which is to keep the discharge difference between simultaneously operating emitters at a maximum of 10 percent. This allows for a 10 to 20 percent variation in pressure head along a lateral, depending on emitter characteristics. A detailed elaboration on various trickle irrigation uniformity concepts may be found in Karmeli et al. (1978).

Efficiency of applying water by trickle irrigation as proposed by Keller and Karmeli (1975) is dependent upon: (a) the transpiration ratio, TR, and (b) the emission uniformity, EU. The transpiration ratio is defined as the ratio of water transpired to water applied to the least watered areas. The emission uniformity as defined by Keller and Karmeli (1975) takes into account the uniformity of emitter discharge throughout a particular system and a method of calculating EU from the manufacturer's rating curve is also presented.

From Karmeli et al. (1978), characteristics of emitters which affect efficiency are: (a) variations in discharge rate due to manufacturing variations; (b) closeness of discharge-pressure relations to design specifications; (c) the emitter discharge exponent, b; (d) possible range of suitable operating pressures; (e) pressure loss in lateral lines due to emitter connections; (f) susceptibility to clogging; and (g) stability of the pressure-discharge relationship over time.

Important design criteria which affect efficiency according to Karmeli et al. (1978) are: (a) efficiency of filtration; (b) permitted variations in pressure head allowed; (c) base operating pressure used; (d) degree of flow (or pressure) control; (e) relationship between discharge and pressure at the control head; (f) allowance for temperature correction in long path emitters; (g) chemical treatment to dissolve mineral deposits; (h) use of secondary safety screening; (i) incorporation of flow measurement; and (j) allowance for reserve system capacity or pressure to compensate for reduced flow due to emitter clogging.

Keller and Karmeli (1975) defined application efficiency, E_a, as:

$$E_a = (TR)(EU) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (96)$$

Good system management on the part of the irrigator is very important in achieving high efficiencies as TR actually depends upon good management. Some excess water is required for leaching and providing a small safety margin. Keller and Karmeli (1975) suggest TR = 0.90 as a reasonable design value for most situations. Although research supports TR's greater than 0.90, TR in many cases has proved to be somewhat less for commercially installed and operated enterprises. This is due to many factors including: (a) contractor inexperience with trickle irrigation; (b) cases where agriculturalists have underdesigned and built their own systems; and (c) irrigator inexperience with trickle system operation and maintenance. Over time, these problems should decrease as more systems are built and operated and additional experience gained.

Values of TR and EU are also used in Keller and Karmeli's (1975) design procedure for computing the gross depth of water application, the irrigation interval, and the required system capacity. EU's of 94 percent or above are desirable and design EU's below 90 percent should not be considered.

TRICKLE IRRIGATION SYSTEM COSTS

Trickle irrigation system costs vary widely due primarily to: (a) type of crop; (b) water source and quality; (c) degree of automation; (d) type of emitter utilized; and (e) other regional factors such as water costs, power costs, and labor (installation) costs.

Individual emitters range in cost from $0.08 to $3.15 each. However, the latter has six potential outlets. Polyethylene pipe (1/2-inch) with ultraviolet radiation protection suitable for surface applications ranges from $0.16 per meter ($0.05 per foot) to $0.28 per meter ($0.086 per foot) depending on quantity. Controllers suitable for the automation of trickle irrigation systems range in cost from $300 to $1500 depending on quality and sophistication. Filtration systems cost from $480 to $16,000 depending on the flow capacity and degree of automation (for backflushing or blowdown).

The initial investment costs for a manually operated system may be as little as $990/hectare ($400/acre). That initial investment cost may increase to approximately $2500/ hectare ($1000/acre) or more for a highly automated system which schedule irrigations as a result of soil moisture data from sensors located in the field.

Assuming a 10 year system life, 8 percent interest, and water costs of $65/hectare-meter ($8/acre-foot), Reed et al. (1977) calculated the annual initial investment costs for a 40-hectare (100-acre) trickle system (in California) as $365/ hectare ($148/acre) after depreciation, interest, and taxes, while the annual operating costs were calculated as $193/hectare ($78/acre). This indicates a total annual cost of $558/hectare ($226/acre) over the ten year life of the system. Due to the large field size and conditions encountered in California, these costs should be considered minimum values.

These costs, however, would be much too low for the Grand Valley because the filtration requirements are very high (due to the large amount of suspended sediment and organic matter in the river water) and the small field sizes. A value of $1800/hectare (Geohring, 1976) would be a better value for use in the Grand Valley area. This is discussed in more detail in Section 12.

EVALUATION OF TRICKLE IRRIGATION IN GRAND VALLEY

As part of this project there were two trickle irrigation systems installed, both for the same grower. One was installed on a peach orchard and the other on an apple orchard. The two separate systems required two system "heads" and two distribution networks; this, of course, considerably increased the per hectare costs. The two systems were installed for $8514 on 2.2 hectares for a $3870 per hectare cost. However, these systems have the capacity to be expanded to cover an additional 5 to 6 hectares with little additional cost resulting in approximately $1800 per hectare cost. In fact, the drip system installed on the apple orchard was designed with the intention of eventually covering an additional 3 hectares. For purposes of this analysis a cost of $2500 per hectare was used which approximates the cost of this installation with only one system head.

As was reported in the preceding report, "Implementation of Agricultural Salinity Control Technology in Grand Valley," (Evans et al., 1978) these trickle irrigation systems were responsible for reducing deep percolation by 0.4 ha-m or reducing salt loading by 17.86 metric tons per year. This resulted in a cost effectiveness of $308 per metric ton removed annually. However, due to the economics of scale and using longer field sizes a cost effectiveness value of $200 per metric ton is more applicable to the Grand Valley for trickle irrigation.

SECTION 12

COMPARISON OF IRRIGATION METHODS FOR SALINITY CONTROL

THE CONCEPT OF COST EFFECTIVENESS

The salinity in irrigation return flows associated with the farm system itself is amenable to improvement by increasing irrigation application efficiencies. In previous sections, irrigation scheduling, rehabilitation and automation of surface irrigation systems, and conversion to sprinkler or trickle irrigation systems are described. In this section, the question of the "best" program to reduce salinity is addressed.

The selection of the "best" or "optimal" on-farm improvements to reduce the volume of return flows is based on a minimum cost criterion in this work. In the Grand Valley, the Federal Government is expected to provide cost-sharing arrangements for the costs incurred in treating the irrigation system. No funds are expected to be forthcoming to pay either operation or maintenance costs associated with the use of the improved systems.

The Federal Government and the Lower Basin water interests affected by the Grand Valley salinity contribution would like to maximize the effectiveness of the program, given the funds appropriated for salinity control. This objective is equivalent to minimizing costs associated with achieving a preselected level of salt loading reductions. At the on-farm level, a number of alternative improvements might be made to improve irrigation efficiency and thereby reduce salinity. Each may be applied to various fractions of the local acreage, resulting in a wide range of expected salinity reductions. The relationship between cost and salinity reduction for a single alternative and expressing the potential range of the alternatives application is called a cost-effectiveness function. For example, let the following relationship represent the cost-effectiveness function for the ith alternative for reducing on-farm salinity.

$$Y_i = f_i(x_i) \; . \quad (97)$$

where Y_i = cost of removing x_i tons of salt through implementing the ith on-farm irrigation system improvement.

The optimal on-farm program is evaluated for a predetermined reduction in the on-farm salinity contributions (x_f) by the following analysis.

$$Y_f = \min_{x_i} \sum_{\ell=1}^{n} f_i(x_i) \quad \ldots\ldots\ldots\ldots\ldots\ldots (98)$$

subject to,

$$\sum_{\ell=1}^{n} x_i \geq x_f \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (99)$$

and,

$$x_i \leq X_i \ , \quad i = 1, 2, \ldots, n \quad \ldots\ldots\ldots\ldots\ldots (100)$$

in which Y_f = the minimum costs of reducing the total on-farm contribution of salinity by x_f tons,

X_i = maximum reduction of salinity possible from the ith alternative, and

n = number of alternative on-farm salinity control options.

The cost-effectiveness relationships are, therefore, the mathematical tools needed to systematically compare the array of alternative on-farm improvements which can be implemented to control salinity. Its use must also incorporate the limits of each alternative's effectiveness (constraints in the optimization analysis, Equation 99. These relationships are the end product of intensive salinity research and their definition represents the transition between research and implementation.

In this study, the writers have selected a somewhat unusual set of units to represent the parameters in the cost-effectiveness functions. Salinity reductions are associated with the control of salt pickup and expressed in metric tons prevented from reaching the Colorado River per year. The costs are the 1976 present value estimates of the capital investments. Thus, the costs are not distributed throughout the life of the improvement. The resulting units of the cost-effectiveness function are dollars per metric ton reduction over the life of the improvements. These units are readily associated with the salinity damages in the Lower Colorado River Basin. Since they only cover the 30-50 year life of the improvements, a reevaluation of the salinity control strategies in the Grand Valley at some time in the future is implied.

The eventual program in the Grand Valley is dictated by its respective feasibility in comparison to similar cost-effectiveness studies on the other subbasins in the Upper Colorado River Basin. In fact, the level of investment in the entire river system for salinity control depends on the level of damages created by the salinity. Since a completed four level analysis is not available, it is interesting to compare downstream damage with costs in the Grand Valley. Note that the estimates of marginal cost and downstream detriments must be the same. Walker (1975) reviewed much of the literature descriptive of the California, Arizona, and Republic of Mexico damages. At the time, Valentine (1974) had proposed damages of $175,000 per mg/ℓ of increase at Imperial Dam ($146 per ton in Grand Valley assuming 8 percent interest). Other estimates in terms of equivalent damages attributable to Grand Valley range upward. A representative figure is $190/ton as proposed by the U.S. Bureau of Reclamation (Leathers and Young, 1976). Some as yet unpublished figures now place these damage figures as high as $375/ton.

SALINITY FROM ON-FARM SOURCES IN THE GRAND VALLEY

The segregation of the Grand Valley water and salt flow system has been presented in several previous publications. Since salinity is exclusively a subsurface return flow process in the Valley, the major components of the on-farm contribution are head ditch and tailwater ditch seepage and deep percolation. The most recent estimates by the writers were presented by Walker et al. (1977), and Walker (1978). The magnitude of the on-farm salinity contribution in the Grand Valley may be summarized in Table 7.

TABLE 7. MAGNITUDE OF THE ON-FARM SALINITY CONTRIBUTION IN THE GRAND VALLEY

	Water Losses[1]	Salt Pickup[2]
head ditch seepage	100.1	95,500
deep percolation	200.1	190,900
tailwater ditch seepage	neglected	0

[1] expressed as millimeters, acreage is 25,000 hectares.

[2] expressed as metric tons, each millimeter of subsurface flow represents 954 metric tons of salt pickup.

The Soil Conservation Service estimates that on-farm ditches contribute 145,250 metric tons to the river system each year and a contribution by deep percolation of 126,800 tons (Kruse, 1977). The Agricultural Research Service estimates that ditch and deep percolation salinity contributions are 103,500 tons and 129,800 tons, respectively (USDA-ARS, 1977; and Kruse, 1977). Thus, the on-farm totals by these three sources are within 20 percent of each other, even though the segregations are somewhat different.

COST-EFFECTIVENESS RELATIONS

The on-farm alternatives for reducing salinity in the Grand Valley can be discussed according to their earlier description: (a) irrigation scheduling; (b) improvements in the existing surface irrigation system; (c) conversion to sprinkle irrigation; and (d) conversion to trickle irrigation. Each alternative is intended to improve the irrigation application efficiency and thereby reduce the volume of on-farm ditch seepage and deep percolation.

Irrigation Scheduling

Recent studies in Grand Valley have indicated that irrigation scheduling services, even when accompanied by flow measurement structures, generally do not significantly improve farm and application efficiencies (Skogerboe et al., 1974b). A west-wide review of irrigation scheduling by Jensen (1975) indicated that a 10 percent improvement (from 40 to 50 percent) is realistically possible without system conversions or more energy intensive operations. In the Grand Valley, a very simple irrigation scheduling service which included water measurement and farmer training would cost an estimated $30/ha and would very optimistically reduce return flow salinity by about 20,000 metric tons annually (Walker et al., 1978). Since it is not known how irrigation efficiencies may be distributed, it is assumed that these figures may be linearly extrapolated yielding a cost-effectiveness function for irrigation scheduling of $37.50/ton with a limit of 20,000 metric tons amenable to this approach.

The overall impact of irrigation scheduling being only 10 percent of the total estimated on-farm potential improvement is insignificant by itself when considering the sensitivity of these types of costing estimates. Consequently, irrigation scheduling should be considered part of other measures rather than a separate individual salinity control measure.

Improving the Existing Surface Irrigation System

Irrigation efficiency can often be substantially improved by rebuilding and remodeling existing systems. The most commonly employed irrigation method in the Valley is the furrow irrigation method. Structural improvements in this system may include concrete lined head ditches or gated pipe to reduce seepage losses, land leveling for better water application uniformity, adjusting field lengths and water application rates to be more congruent with soil and cropping conditions, changing to a border irrigation method, and automation to provide better control. Flow measurement and scheduling services should accompany these types of improvements in order to maximize their effectiveness.

In the Grand Valley, head ditch requirements are generally less than the capacity of the smallest standard ditch available through local contractors (12 inch, 1:1 side slope, slip form concrete). A cost figure for concrete lining of this size, well within the range encountered in the last two seasons in the Valley, is about $7.50/meter (1975 cost base). Six-inch diameter aluminum gated pipe, which would carry about the same flows, would cost approximately the same and can be arbitrarily substituted with equal cost-effectiveness. There are approximately 1.3 million meters of head ditches in the Grand Valley contributing an estimated 95,500 metric tons of salt to the river annually. If linings were assumed to be 90 percent effective (0.9 x 95,500 = 86,000), the cost-effectiveness of head ditch improvements would be $113.40/ton (1.3 million meters x $7.50/m ÷ 86,000 tons).

Automatic cut-back furrow irrigation systems have demonstrated improved application efficiencies of 75 or 80 percent (Evans, 1977), thereby affecting an additional 60,000 ton decrease beyond the effects of the linings. In 1975, the installed cost of the cut-back systems was $11.50/m. Thus, the salt load reductions by lining head ditch (86,000 tons) and the additional 60,000 metric ton salt reduction resulting from increased application efficiency yields a cost-effectiveness of $102.40/ton. Because of the small size of these ditches, a linear distribution can be assumed without introducing significant error. In the case of the Grand Valley, it appears automation may be added to surface irrigation systems for the purpose of increasing application efficiency at about the same cost-effectiveness as the simple head ditch or gated pipe improvements ($113.40/ton compared with $102.40/ton).

Field lengths can be modified and the fields leveled to improve the uniformity of the water applications under surface irrigation, particularly in soils having a relatively high infiltration capacity. In the Grand Valley, however, the soils have a low infiltration capacity, and the fields have a 1 to 2 percent slope so that the control of lateral flow distributions are adequately made by the furrows. Uniformities are already high and could be improved by varying the furrow flow rate such as with a cut-back system. It is unlikely, therefore, that land leveling or adjusting the field geometry should even be considered. Furthermore, local trials with border irrigation, where land leveling and field length adjustments are necessary, did not indicate higher application efficiencies than those already achievable. Consequently, these on-farm improvements appear infeasible at this time in the Grand Valley.

System Conversion

In order to completely control irrigation return flows, the method of applying irrigation water needs to be independent of soil properties (i.e., sprinkler and trickle irrigation systems). In earlier sections, the sprinkler irrigation application efficiency was shown to be approximately 80 percent. Trickle systems could be expected to operate at the 90 percent level. Applying sprinkler systems to the average field size in the Grand Valley (2-3 hectares) would be very expensive, so most systems would only irrigate the larger or multiple fields. An estimate of the area dependent costs of various sprinkler and trickle irrigation systems is given in Figure 49, which indicates that portable sprinkler irrigation systems (side-roll and hand-move) would cost about \$900 per hectare for a coverage of 10 hectares and \$600 per hectare if these areas were doubled. According to Walker et al. (1977), 90 percent of the Grand Valley fields are less than 10 hectares so that the \$900 per hectare side-roll sprinkler cost is probably a conservative figure. Trickle irrigation systems would cost approximately \$1,800 per hectare for most local field sizes (Geohring, 1976). Assuming irrigators would consolidate fields sufficiently to avoid the high costs for irrigating small fields, and assuming application efficiencies of 80 percent and 90 percent for sprinkler and trickler systems, respectively, the salt loading reduction for each system can be calculated as follows (an existing application efficiency of 64 percent is determined from the valley hydro-salinity data):

$$\mathrm{SLR} = \mathrm{SCDS} + \frac{\mathrm{TOFS}}{\mathrm{TA}} \left(1 - \left[\frac{1-\mathrm{AE}}{1-0.64}\right]\right) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (101)$$

where,

SLR = tons of salt load reduction per hectare;
SCDS = tons of salt reduction per hectare assuming the pressurized systems eliminate head ditches;
TOFS = total on-farm salinity, 190,900 tons;
TA = total irrigated acreage, 25,000 ha; and
AE = application efficiency expressed as a fraction.

Thus, for sprinkler systems the per hectare salt decrease is 6.84 tons and for trickle irrigation systems, 8.96 tons. Mobile or portable sprinkler systems would have average salinity cost-effectiveness ratios of between \$131.58/ton (assuming \$900/ha capital cost), while the costs for trickle systems would be about \$200.89/ton. Solid-set sprinklers would be at least double these figures and are, therefore, not evaluated. Center-pivot systems would be difficult to apply in the Grand Valley because of the small average size of land holdings.

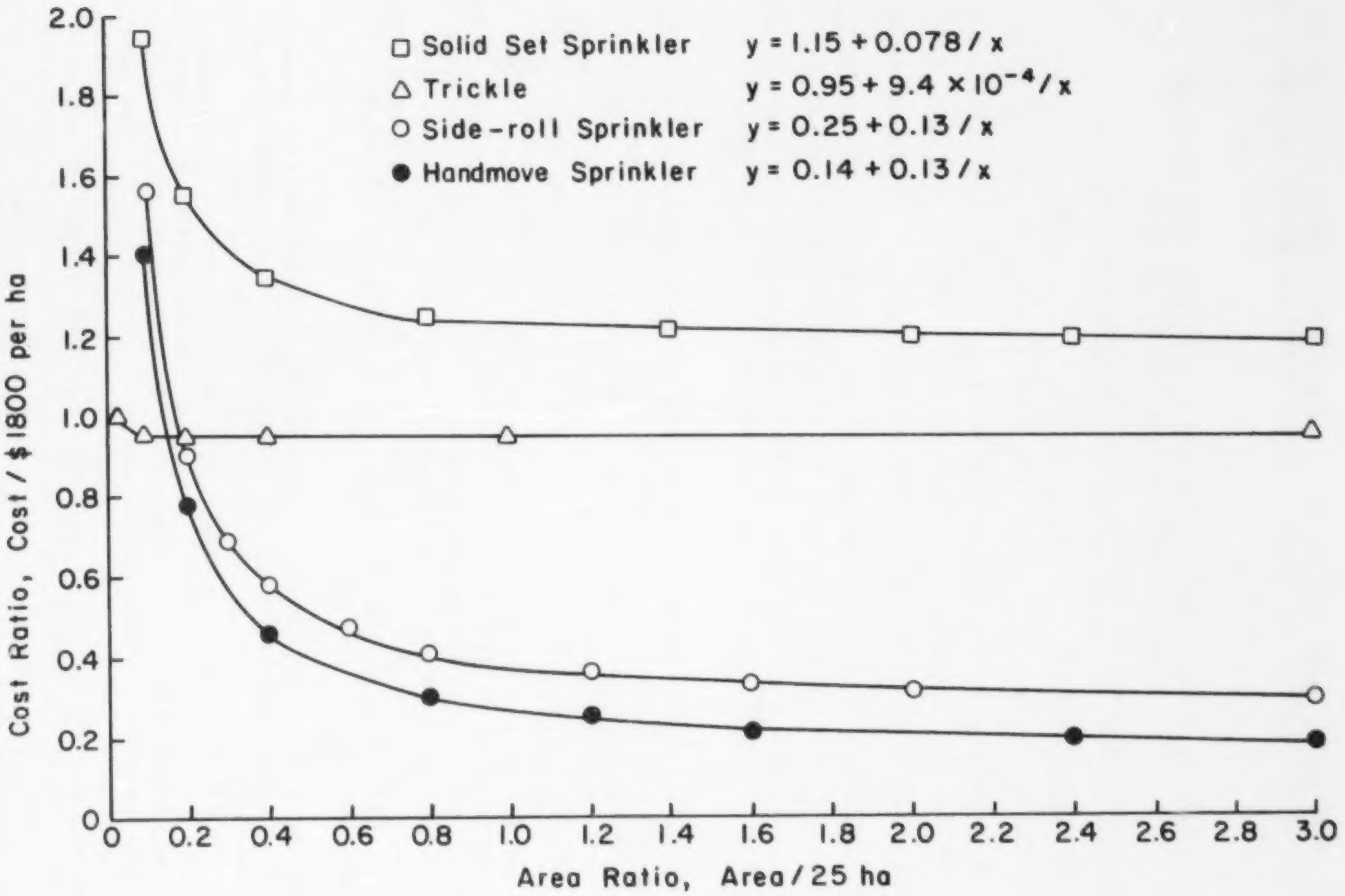


Figure 49. Cost relationships for pressurized irrigation systems (Walker, 1978).

OPTIMAL ON-FARM STRATEGIES

A summary of the individual cost-effectiveness functions for the various alternative on-farm improvements are given in Table 8.

TABLE 8. COST-EFFECTIVENESS FUNCTIONS FOR ON-FARM IMPROVEMENTS IN THE GRAND VALLEY

Alternative[1]	Function[2]	Limitations[2]
1) head ditch lining	$Y_{hd} = 113.40\ X_{hd}$	$X_{hd} \leq$ 86,000 tons
2) No. 1 + automation	$Y_{cb} = 102.40\ X_{cb}$	$X_{cb} \leq$ 146,000 tons
3) sprinkler irrigation	$Y_s = 131.58\ X_s$	$X_s \leq$ 171,000 tons
4) trickle irrigation	$Y_t = 200.89\ X_t$	$X_t \leq$ 224,000 tons

[1] irrigation scheduling assumed to be part of each alternative.

[2] subscripts are defined as: hd = head ditches; cb = automated cut-back irrigation; s = sprinkler; and t = trickle.

The optimal on-farm program is developed by computing the minimum cost strategy at various levels of on-farm salinity reductions using the relationships summarized above. The results shown in Figure 50 are those presented by Walker (1978) which aggregate the head ditch linings into the automated case. The actually computed cost-effectiveness relationship for on-farm improvements is the step function shown as the solid lines. The broken curve represents a best fit nonlinear distribution. The assumption of linear or average cost-effectiveness functions was made originally to alleviate the difficulty in defining the variability experienced in the real system. The nonlinear curve helps reestablish the curvilinear characteristic of such relationships.

The best on-farm improvements in the Grand Valley shown in Figure 50 might be discussed in terms of an implementation of better on-farm irrigation practices in the Grand Valley. About 50 percent of the salt loading presently occurring from over-irrigation can be reduced by lining and automating the farm head ditches with concrete or gated pipe, and then carefully following irrigation scheduling recommendations. The value of the automation is that the labor requirement in more careful irrigations is eliminated, and by so doing, irrigation efficiencies can be increased. This is the simplest and least costly alternative in the Grand Valley. Sprinkler irrigation systems can be introduced if it is decided that the on-farm salinity contribution must be

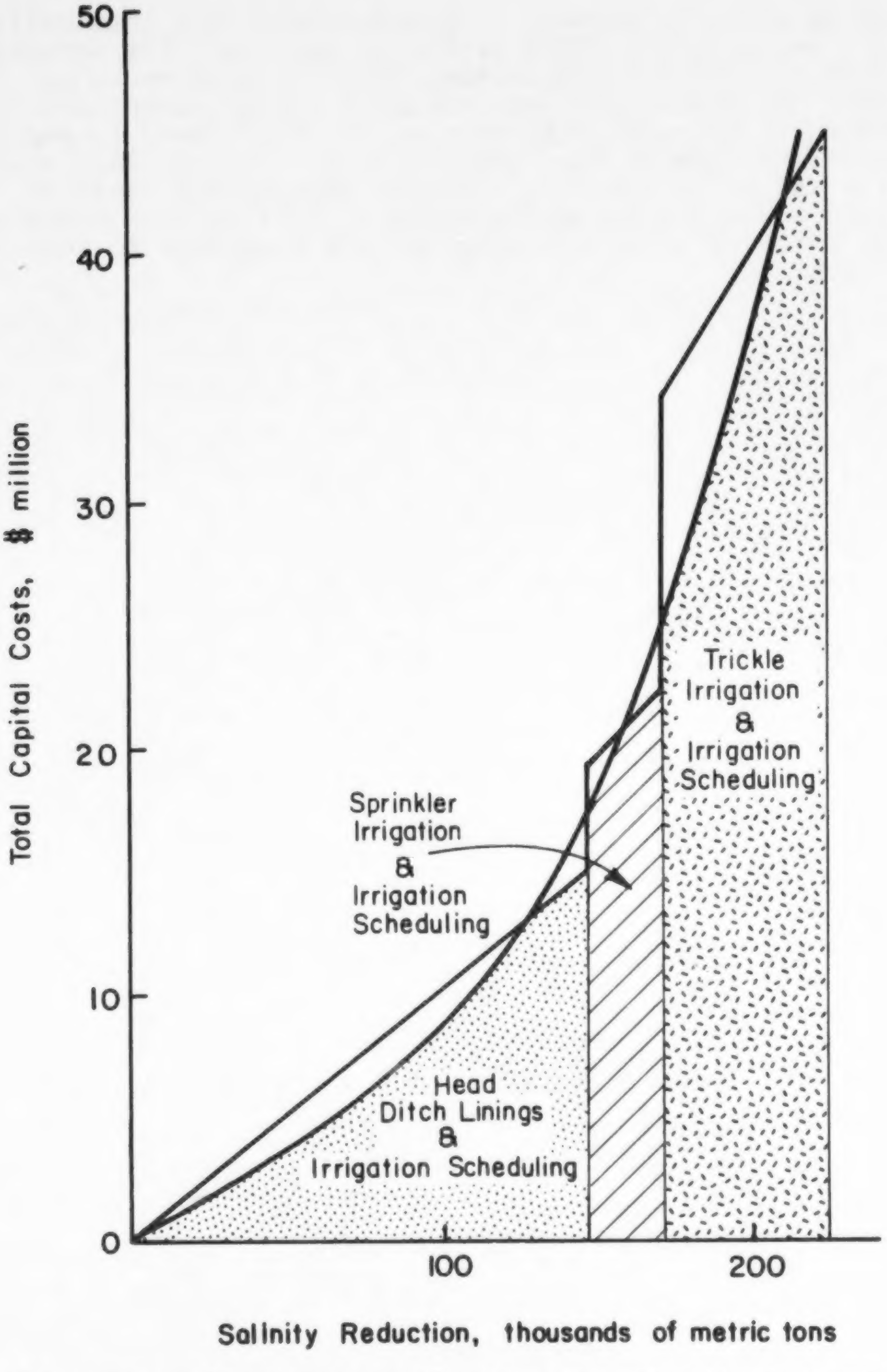


Figure 50. Cost-effectiveness function for the first level, on-farm improvement alternatives, in the Grand Valley (Walker, 1978).

reduced by about 60 percent (171,000 metric tons annually). However, the existing field sizing is too small for economical sprinkler systems and substantial consolidation would be required. No costs have been assigned to the consolidation requirement. Trickle irrigation can be introduced to expand on-farm salinity control from 171,000 tons to about 224,000 tons annually (60 to 78 percent). Again, farming and cropping practices would require modification. It should be noted that several forms of trickle irrigation are available to meet various farmer desires.

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